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SHOCK WAVE PROPAGATION THROUGH AERATED WATER

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The objective of the research described here was to measure the shock and bubble characteristics in aerated water and water that is approximately air-free. For these measurements, we used SRI’s water shock pool facility located at Corral Hollow Experiment Site (CHES) near Tracy, California. Obtaining SZ-like aerated water characteristics with respect to bubble size and air content required conducting the experiments in saltwater; thus, salt was added to the CHES pool facility to bring the density up to 1.022 g/cm^3, which is representative of ocean seawater. To generate aerated water in the pool, we flowed gas through a bass wood bubble generator located on the pool bottom. The experiments were conducted in aerated water with an air-content of approximately 1.6% ±0.2%. Pressure measurements were made at 6.1, 8.1, and 12.5 inches from a 49-g Comp B explosive charge. With respect to air-free water, the shock peak pressure, impulse, and energy in the aerated water were reduced by factors of approximately 2.9, 1.2, and 3.3, respectively. The explosive charge bubble peak pressure, impulse, and energy were reduced by factors of 2.0, 1.4, and 2.6, respectively.

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FOREWORD

The work described in this final technical report was performed by SRI International for the Indian Head Division, Naval Surface Warfare Center (IHDIV, NSWC) under Contract Number N00174-99-M-0219. The IHDIV, NSWC Technical Monitor was Mr. Daniel T. Tam.

Mr. Paul R. Gefken was the SRI project Supervisor. Mr. Gary Greenfield, who was the SRI Project Leader, developed the technology for generating surf zone (SZ) like bubbles and the technology for cost-effectively measuring the air content in aerated water. Special thanks are given to Mr. Bob Borunda for conducting the experiments in which explosive shock and bubble characteristics were measured in an aerated water medium.

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ABSTRACT

The surf zone (SZ) consists of a mixture of water and air resulting from the turbulent action of wave motion. This water-air mixture will have different shock wave propagation characteristics than a water medium that is air-free. Shock wave propagation in the aerated water SZ medium is important to the Navy because many of the threat targets, such as mines and obstacles, are located in the SZ.

The objective of the research described here was to measure the shock and bubble characteristics in aerated water and water that is approximately air-free. For these measurements, we used SRI's water shock pool facility located at Corral Hollow Experiment Site (CHES) near Tracy, California. Obtaining SZ-like aerated water characteristics with respect to bubble size and air content required conducting the experiments in saltwater; thus, salt was added to the CHES pool facility to bring the density up to 1.022 g/cm^3, which is representative of ocean seawater. To generate aerated water in the pool, we flowed gas through a bass wood bubble generator located on the pool bottom.

The experiments were conduced in aerated water with an air content of approximately 1.6% $\pm$ 0.2%. Pressure measurements were made at 6.1, 8.1, and 12.5 inches from a 49-g Comp B explosive charge.

With respect to air-free water, the shock peak pressure, impulse, and energy in the aerated water were reduced by factors of approximately 2.9, 1.2, and 3.3, respectively. The explosive charge bubble peak pressure, impulse, and energy were reduced by factors of 2.0, 1.4, and 2.6, respectively.

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CHAPTER 1

INTRODUCTION AND SUMMARY

1.1 Background and Objective

The surf zone (SZ) consists of a mixture of water and air resulting from the turbulent action of wave motion. This water-air mixture will have different shock wave propagation characteristics than a water medium that is air-free. Shock wave propagation in the aerated water SZ medium is important to the Navy because many of the threat targets, such as mines and obstacles, are located in the SZ. However, many of the Navy weapon systems designed to defeat these targets have been characterized in water mediums that are nearly air-free. Preliminary computations performed by Indian Head Division, Naval Surface Warfare Center have shown that the shock peak pressure will be reduced by as much as a factor of 2 in water with 2% air.

Fully characterizing the effects of aerated water on water shock and bubble properties requires an extensive program composed of precision experiments and computations. A key requirement of the experiments is that the aerated water properties are well characterized with respect to bubble size and air content. This information is necessary to fully validate the computational models used to predict the aerated water effects on the shock and bubble characteristics for a wide range of SZ aerated water conditions and, ultimately, the effects on target damage.

The objectives of the research described here were to perform a series of experiments to scope the shock and bubble characteristics in aerated water and to determine the potential magnitude of the difference between these values and the values measured in approximately air- free water.

1.2 Approach

Our approach consisted of developing a bubble generator to aerate the water in SRI's water shock pool facility located at Corral Hollow Experiment Site (CHES) near Tracy, California. Obtaining the SZ-like aerated water characteristics with respect to bubble size and air content required conducting the experiments in saltwater; thus, salt was added to the CHES pool facility to bring the density up to 1.022 g/cm^3, which is representative of ocean seawater. The shock and bubble characteristics were measured at various standoffs from a 49-g Comp B explosive charge in aerated saltwater and in saltwater that is air-free.

1.3 Report Organization

Chapter 2 describes the experimental technique for generating and characterizing SZ-like aerated water. Chapter 3 presents the experimental results, which show comparisons between shock and bubble characteristics in aerated water and air-free water.

1.4 Summary of Results and Future Work

Five experiments were performed consisting of one experiment in air-free saltwater and four experiments in aerated saltwater. Typically the water temperature was 69.3ºF. The air-free saltwater had a sound velocity of 5150 ft/s (1570 m/s). The aerated water experiments were performed with a nominal bubble diameter of 0.01 in. and an air content of approximately 1.6% ± 0.2%. The aerated water sound velocity was 4855 ft/s (1480 m/s).

Pressure measurements were made at 6.1, 8.1 and 12.5 in. from a 49-g Comp B explosive charge. With respect to air-free water, the shock peak pressure, impulse, and energy in the aerated water were reduced by factors of approximately 2.9, 1.2, and 3.3, respectively. The explosive charge bubble peak pressure, impulse, and energy were reduced by factors of 2.0, 1.4, and 2.6, respectively.

The experimental results were generated in a confined aerated water column with a diameter between 24 to 36 in. Due to the fact that the proximity of the boundary between the aerated water and air-free water may have influenced the results, we recommend that future experiments be conducted with a larger aerated water region. By placing more bubble generator units on the bottom of SRI's water shock pool facility, we can produce an aerated water region between 15 to 30 ft square. This aerated water region would also be useful for evaluating line charges associated with specific Navy weapon systems.

Future experiments should also establish the relationship between different air contents ranging from 0.5% to 2% and the decrease in water shock and bubble characteristics. Experiments should also be performed with targets such as SZ mines in the aerated water to evaluate the load-damage relationship.

CHAPTER 2

EXPERIMENTAL TECHNIQUE

2.1 Laboratory Aerated Water Experiments

Laboratory size experiments were conducted to determine the optimum technique for generating SZ-like aerated water. Ideally, the aerated water should have 0.004- to 0.008-in.-diameter bubbles and an air content ranging from 0.5% to 2%. To generate the air bubbles, we used the technique of flowing gas through wood.[11] Walnut produced bubble sizes near the bubble diameter of interest. However, 30 to 60 psi was required to obtain the desired air content of 0.5% to 2% and the grain distribution was uneven in large quantities. Because the large required gas pressure would necessitate fabricating a robust support structure for a bubble generator size of 36-in.-square and the uneven grain distribution would produce a combination of small and large bubbles, we chose not to use walnut. Through experiments on different types of woods, we found that basswood had the optimum performance characteristics. The basswood requires only 0.5 to 1 psi to generate the desired air content and the grain distribution is fine and uniform over a large surface area.

Another important parameter that influences bubble diameter is the type of aerated water. The bubble diameter in fresh water ranged from 0.01 in. to 0.1 in. as shown in Figure 2-1A. Furthermore, the bubble field in fresh water contains many large regions where no bubbles are present. In saltwater with a density of 1.022 g/cm^3, the bubble diameters are mostly less than 0.01 in. as shown in Figure 1-2B, and the bubbles are uniformly spaced close together such that the bubble field has a cloudy white appearance. Adding 0.05% concentration of soap to the water produced the same bubble characteristics as saltwater. Thus, it is hypothesized that saltwater and soapy water produce smaller and more uniform bubbles than fresh water because of lower water surface tension. Based on these findings, we added 15,000 pounds of salt to our water shock pool facility at CHES to replicate ocean conditions and bring the water density up to 1.022 g/cm^3.

2.2 Experimental Arrangement

Figure 2-2 shows the 36-in.-square bubble generator used in the experiments. The bubble generator is composed of 50 individual bass wood blocks positioned so that the end grain faces upward. Nitrogen gas is passed through each block from the bottom. The bubble generator requires approximately 0.5 to 1 psi above the hydrostatic pressure to generate a bubble field with an air content of approximately 1.6%.

Figure 2-3 shows the SRI saltwater pool facility. The pool is approximately 30-ft square by 13-ft deep and has tapered sides. The bubble generator was placed on the pool bottom with a water head of approximately 12-ft as shown in Figure 2-4. Thus, approximately 5.5 to 6 psi was used to pressurize the bubble generator to obtain an air content of 1.6%.

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[1] Smith, P. J., *Testing Various Materials for Producing Bubbles*, NSWC Department 40 Technical Report (unpublished).

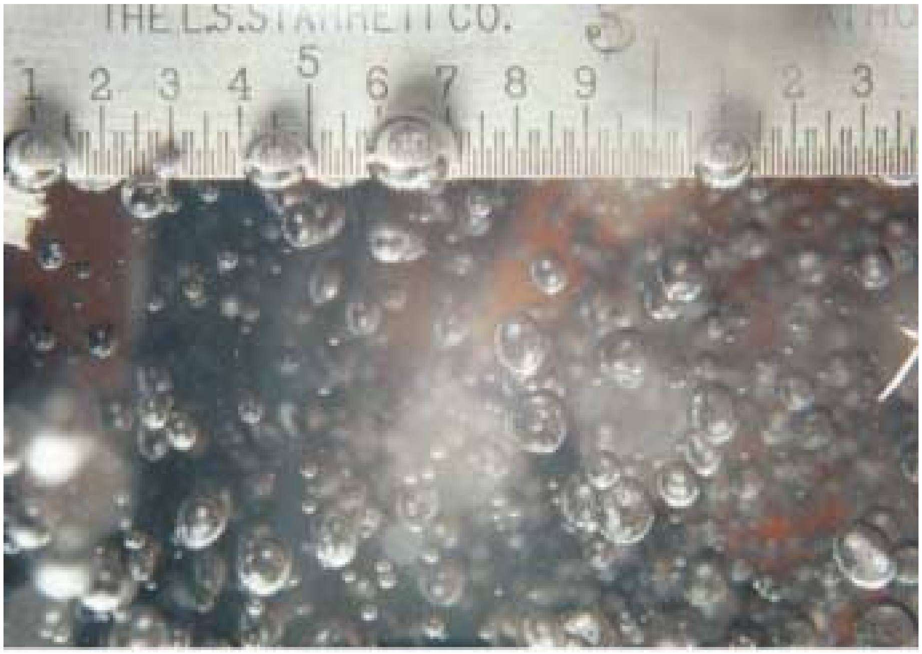
Figure 2-5 shows an underwater photograph of a close-up view of the bubble generator during operation. Figure 2-6 shows an underwater photograph of a wide-angle view of the bubble field from the pool bottom to the surface. The hydrostatic pressure compresses the bubble field from a 36-in.-square to approximately a 20-in.-diameter column in the first 2-ft above the bubble generator. Above this location, the bubble field remains a uniform column as shown in Figure 2-6.

The charge consisted of 49 g of Comp B explosive with a spherical diameter of 1.52 in. The charge was center-initiated using a standard RP80 detonator. PCB 138M tourmaline pressure gauges were placed at standoff distances from the charge of 6.1 in., 8.1 in., and 12.5 in. as shown in Figure 2-7. In each experiment, the charge and pressure gauges were positioned at a depth of approximately 5-ft.
Because the bubbles tended to adhere to the pressure gauges, the gauges were coated with Rainx to reduce the surface tension between the gauges and the bubbles. Figure 2-8 shows the Rainx-coated tourmaline pressure gauge after being in the bubble field shown in Figure 2-6. Only a few bubbles remain attached, indicating that the Rainx coating effectively eliminated the adhering of bubbles on the gauge.

2.3 Aerated Water Characterization Technique

To characterize the sound velocity in the saltwater with and without entrained air, we positioned two Panametrics videoscan immersion transducers at a known distance from each other. Figure 2-9 shows the sound velocity measurement setup. The measured sound velocity in saltwater with no air was 5150 ft/s (1570 m/s), and the measured sound velocity in aerated saltwater with 1.6% air content was 4855 ft/s (1480 m/s).

Figure 2-10 shows the apparatus designed and constructed at SRI for measuring the air content of the water. The apparatus consists of a tube with pneumatic closure units at each end. The closure units each operate at the same time from a single control switch. The measurement process consists of placing the tube with the ends opened in the aerated water and then closing the ends. Given that the ends close at the same time, an aerated water sample is contained within the tube. By measuring the air void after the bubbles have migrated to the surface, we can estimate the air content. The error of the measurement technique is estimated to be ± 0.2%.



(a) - Bubble Characteristics in Fresh Water

(b) - Bubble Characteristics in Saltwater

FIGURE 2-1. BUBBLE CHARACTERISTICS IN FRESH AND SALTWATER

FIGURE 2-2. 36-INCH SQUARE BUBBLE GENERATOR

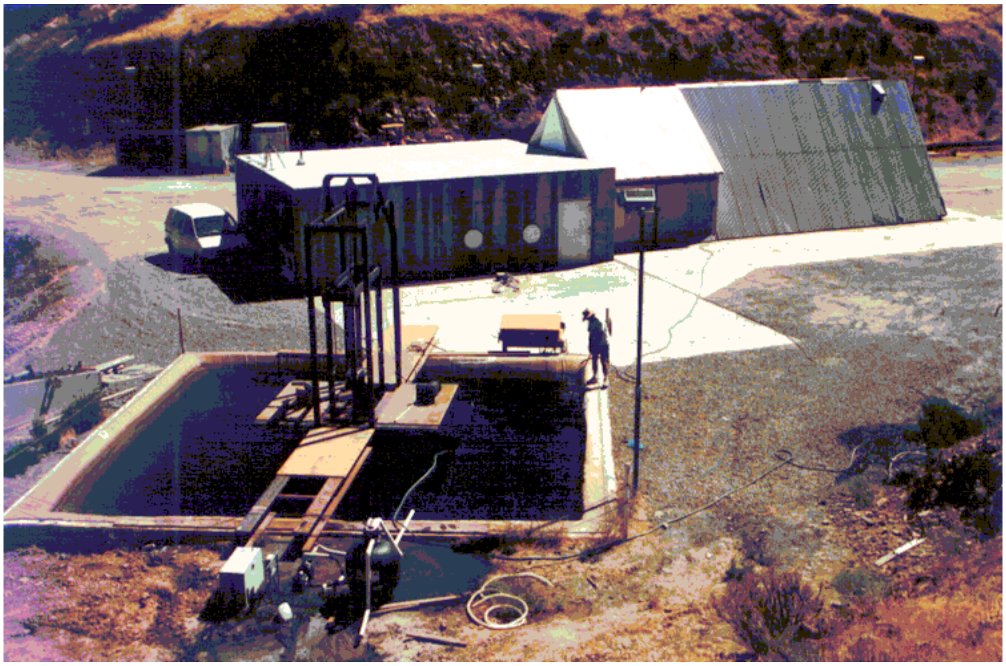


FIGURE 2-3. SRI SALTWATER POOL FACILITY

FIGURE 2-4. BUBBLE GENERATOR POSITIONED ON POOL BOTTOM

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FIGURE 2-7. PRESSURE GAGE POSITION RELATIVE TO CHARGE

FIGURE 2-8. BUBBLE ADHESION TO A PRESSURE GAGE WITH RAINX APPLICATION

FIGURE 2-9. HYDROPHONE TRANSDUCERS FOR SOUND SPEED MEASUREMENTS

FIGURE 2-10. AIR CONTENT WATER SAMPLER

CHAPTER 3

EXPERIMENTAL RESULTS

Five experiments were performed consisting of one experiment in air-free saltwater (Experiment FF1) and four experiments in aerated saltwater (Experiments BW1 – BW4). Typically, the water temperature was 69.3ºF. In Experiment BW2, the explosive charge is believed to have misfired; thus, the results are not presented here. In Experiments BW1, BW3, and BW4 the bubble generator was operated with a pressure of 5.5 psi to produce aerated water with 1.6 $\pm$ 0.2% air content. In Experiment FF1, the measured sound velocity was 5150 ft/s (1570 m/s), and in Experiments BW1, BW3, and BW4 the measured sound velocity was 4855 ft/s (1480 m/s).

3.1 Shock Wave Characteristics

Figures 3-1 through 3-12 shows the shock pressure-, impulse-, and energy-time histories measured in each experiment. In experiment FF1, no pressure record was obtained for the gauge at the 6.1-in. standoff from the charge. Table 3-1 presents the shock time-of-arrivals (TOA), peak pressures, impulses, and energies from each experiment. Although the water air content was approximately the same in experiments BW1, BW3, and BW4, the TOA, peak pressure, impulse, and energy values differ by factors of 1.4, 2.5, 1.3, and 2.5, respectively, between the three experiments. The poor reproducibility in the aerated water experiments may be a function of variations in the air content uniformity within the bubble field. Furthermore, the effects of the boundary between the aerated water and air-free water would influence the measurements approximately 300 μs after wave arrival.

Comparison of the results between Experiment FF1 and the average of Experiments BW1, BW3, and BW4 suggests that the shock wave speed, peak pressure, impulse, and energy are approximately factors of 1.3, 1.9-2.9, 1.0-1.2, and 2.5-3.3 less in aerated water with 1.6% air content, respectively. Figures 3-13 through 3-15 show the shock peak pressure, impulse, and energy attenuation with range. The shock peak pressure and energy show a larger attenuation in the aerated water with 1.6% air content as compared to air-free water. However, the shock impulse attenuation in the aerated water is nearly the same as in the air-free water.

3.2 Bubble Characteristics

Figures 3-16 through 3-24 shows the bubble pressure-, impulse-, and energy-time histories measured in each experiment. Table 3-2 presents the bubble TOA, peak pressure, impulse, and energy values. The bubble pulse in the aerated water arrives 2 ms before the bubble pulse in the air-free water indicating a lower bubble period and radius. Comparison of the results of Experiment FF1 and the average of Experiments BW1, BW3, and BW4 suggests that the bubble peak pressure, impulse, and energy are approximately factors of 1.8-2.0, 1.1-1.4, and 1.9-2.6, less in aerated water with 1.6% air content, respectively.

TABLE 3-1. SUMMARY OF SHOCK WAVE PROPERTIES

	TOA (μs)	Peak Pressure (psi)	Impulse (psi-s)	Energy (in.-lb/in.^{2})
Range = 6.1 in.				
Experiment FF1	NA	NA	NA	NA
Experiment BW1	78	16,000	0.73	772
Experiment BW3	76	21,000	1.08	1217
Experiment BW4	NA	NA	NA	NA
Range = 8.1 in.				
Experiment FF1	102	16,400	0.98	875
Experiment BW1	121	7,400	0.89	300
Experiment BW3	107	13,000	0.83	538
Experiment BW4	129	5,800	0.71	212
Range = 12.5 in.				
Experiment FF1	173	9,800	0.56	327
Experiment BW1	224	2,600	0.66	88
Experiment BW3	175	5,400	0.56	133
Experiment BW4	237	2,200	0.49	61

TABLE 3-2. SUMMARY OF BUBBLE PROPERTIES

	TOA (ms)	Peak Pressure (psi)	Impulse (psi-s)	Energy (in.-lb/in.^{2})
Range = 6.1 in.				
Experiment FF1	NA	NA	NA	NA
Experiment BW1	98	2700	1.31	297
Experiment BW3	NA	NA	NA	NA
Experiment BW4	NA	NA	NA	NA
Range = 8.1 in.				
Experiment FF1	98	3800	1.44	387
Experiment BW1	96	1900	1.00	150
Experiment BW3	96	2100	1.01	166
Experiment BW4	93	1500	1.06	123
Range = 12.5 in.				
Experiment FF1	99	2300	1.07	165
Experiment BW1	96	1600	1.19	136
Experiment BW3	96	1400	1.14	87
Experiment BW4	92	900	0.63	44

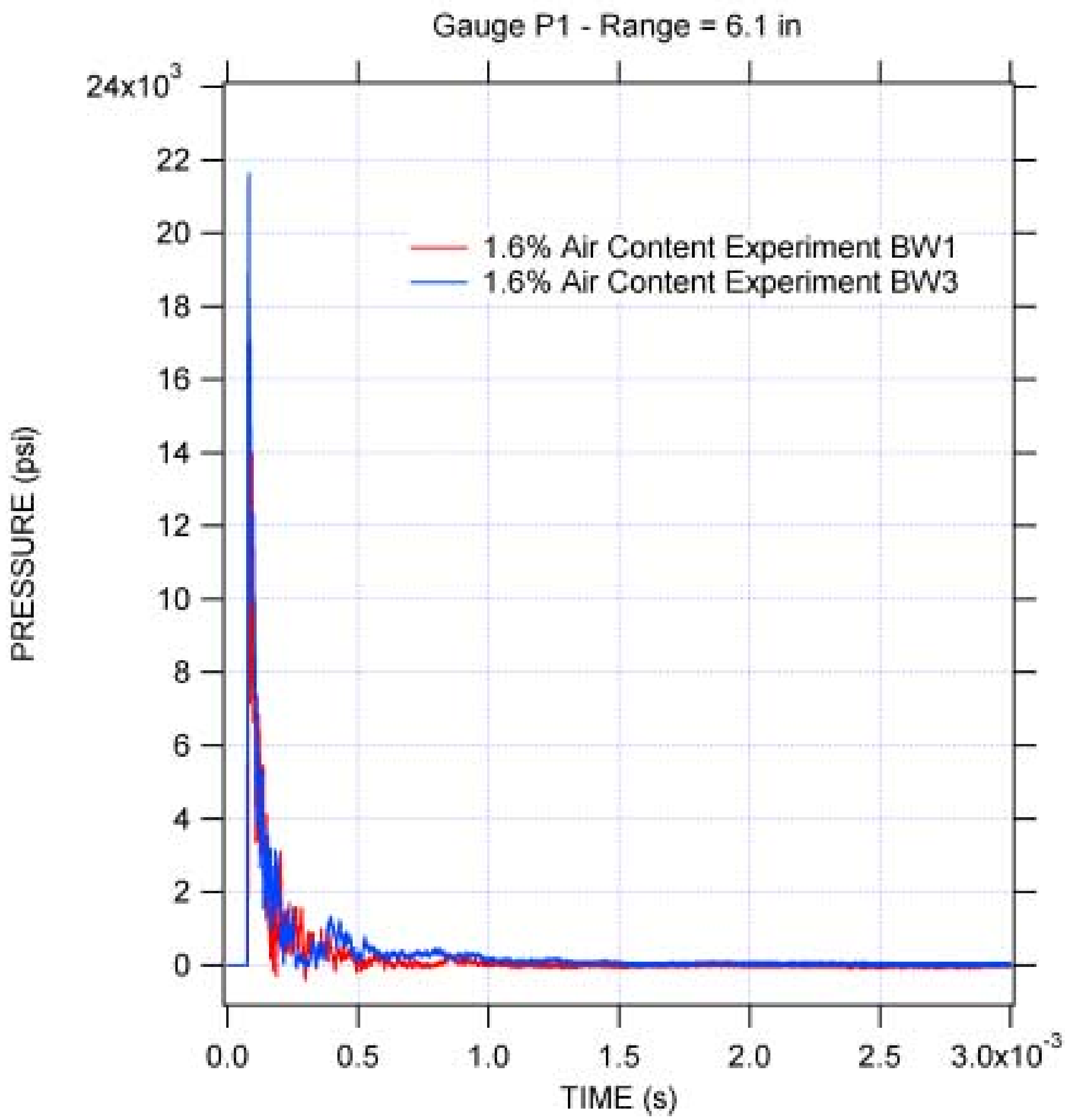

FIGURE 3-1. SHOCK PRESSURE–TIME HISTORY AT 6.1 IN. STANDOFF FROM CHARGE (3 ms TIME WINDOW)

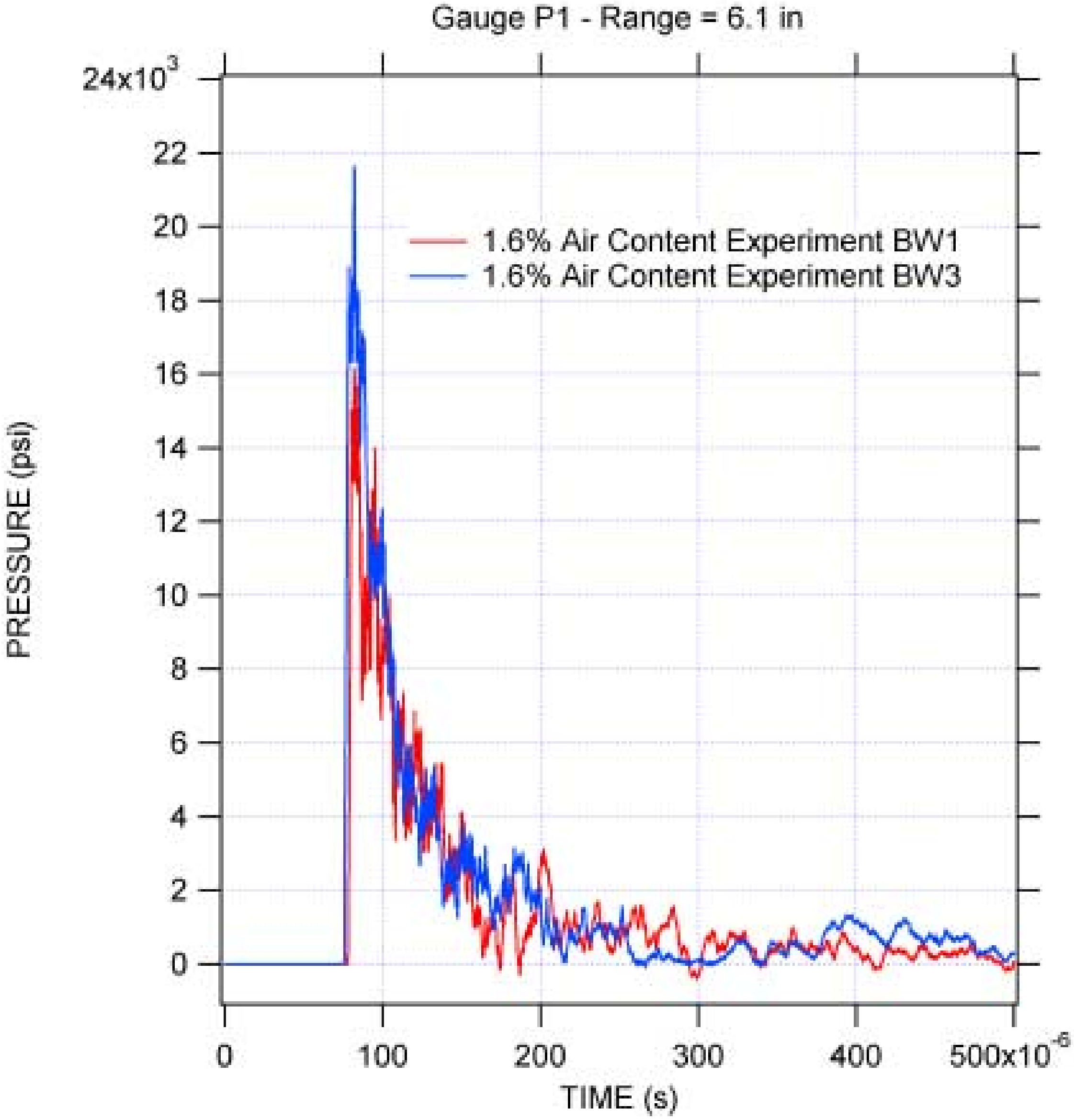

FIGURE 3-2. SHOCK PRESSURE–TIME HISTORY AT 6.1 IN. STANDOFF FROM CHARGE (500 μs TIME WINDOW)

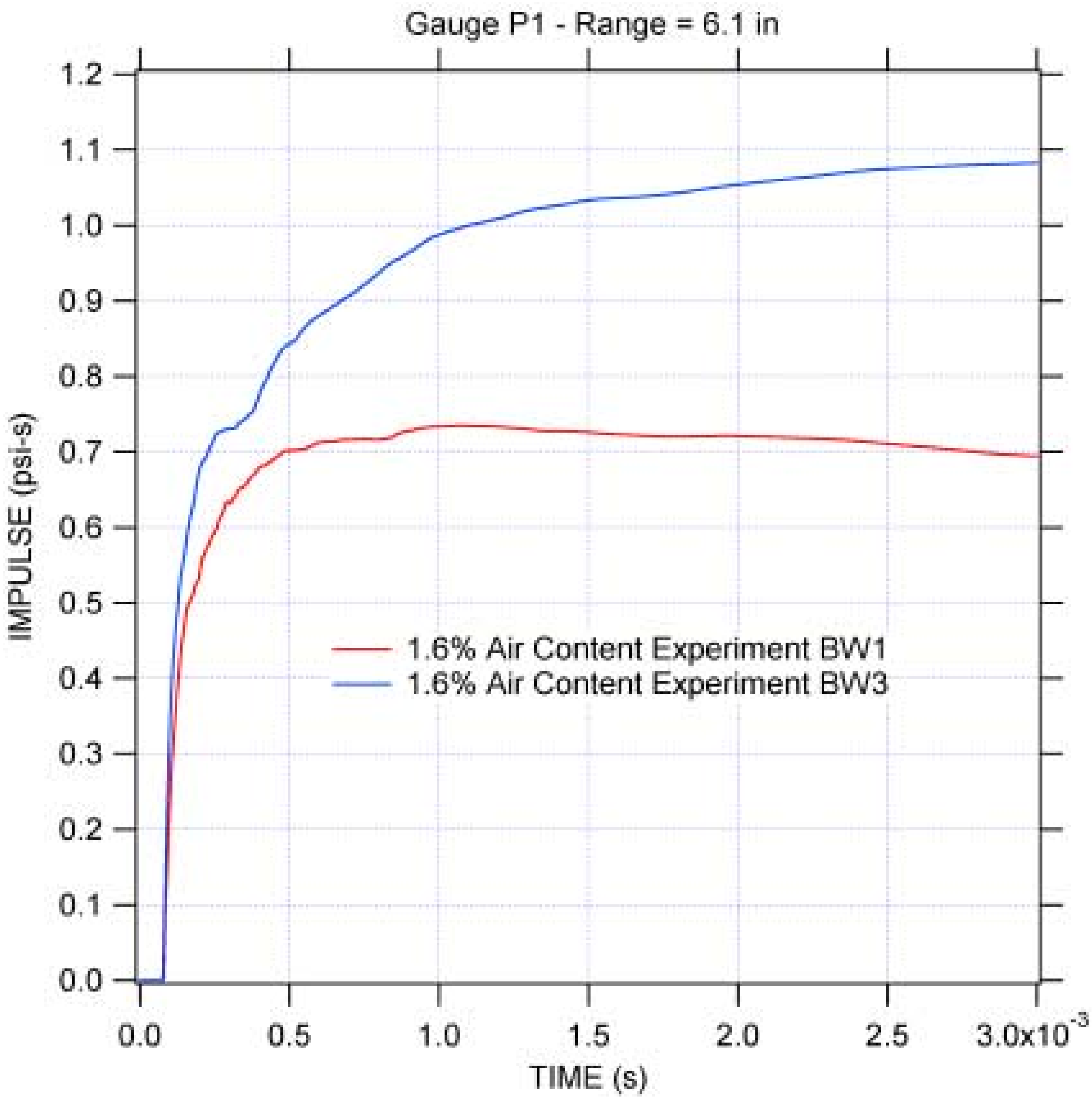

FIGURE 3-3. SHOCK IMPULSE–TIME HISTORY AT 6.1 IN. STANDOFF FROM CHARGE

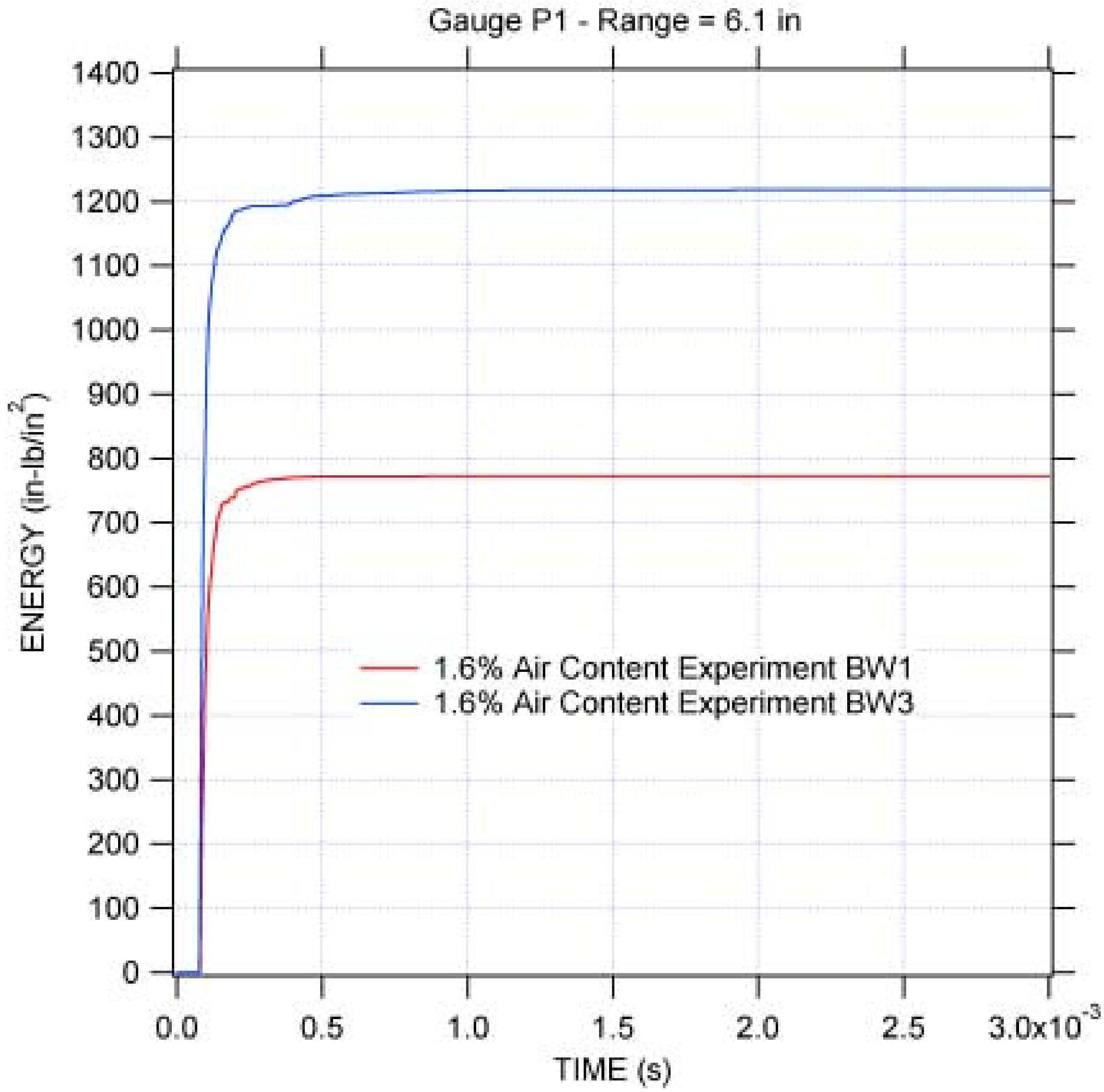

FIGURE 3-4. SHOCK ENERGY–TIME HISTORY AT 6.1 IN. STANDOFF FROM CHARGE

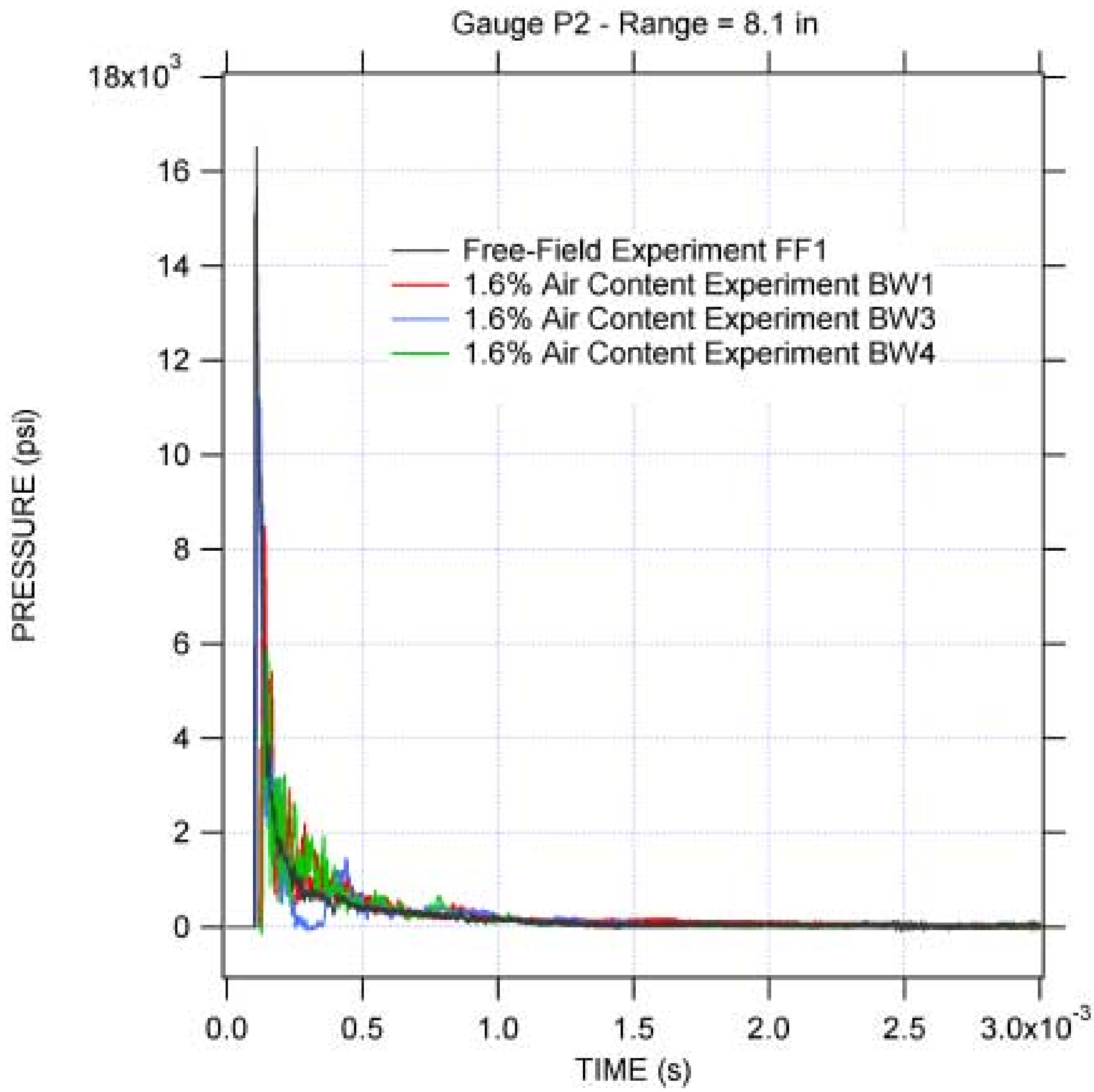

FIGURE 3-5. SHOCK PRESSURE-TIME HISTORY AT 8.1 IN. STANDOFF FROM CHARGE (3 ms TIME WINDOW)

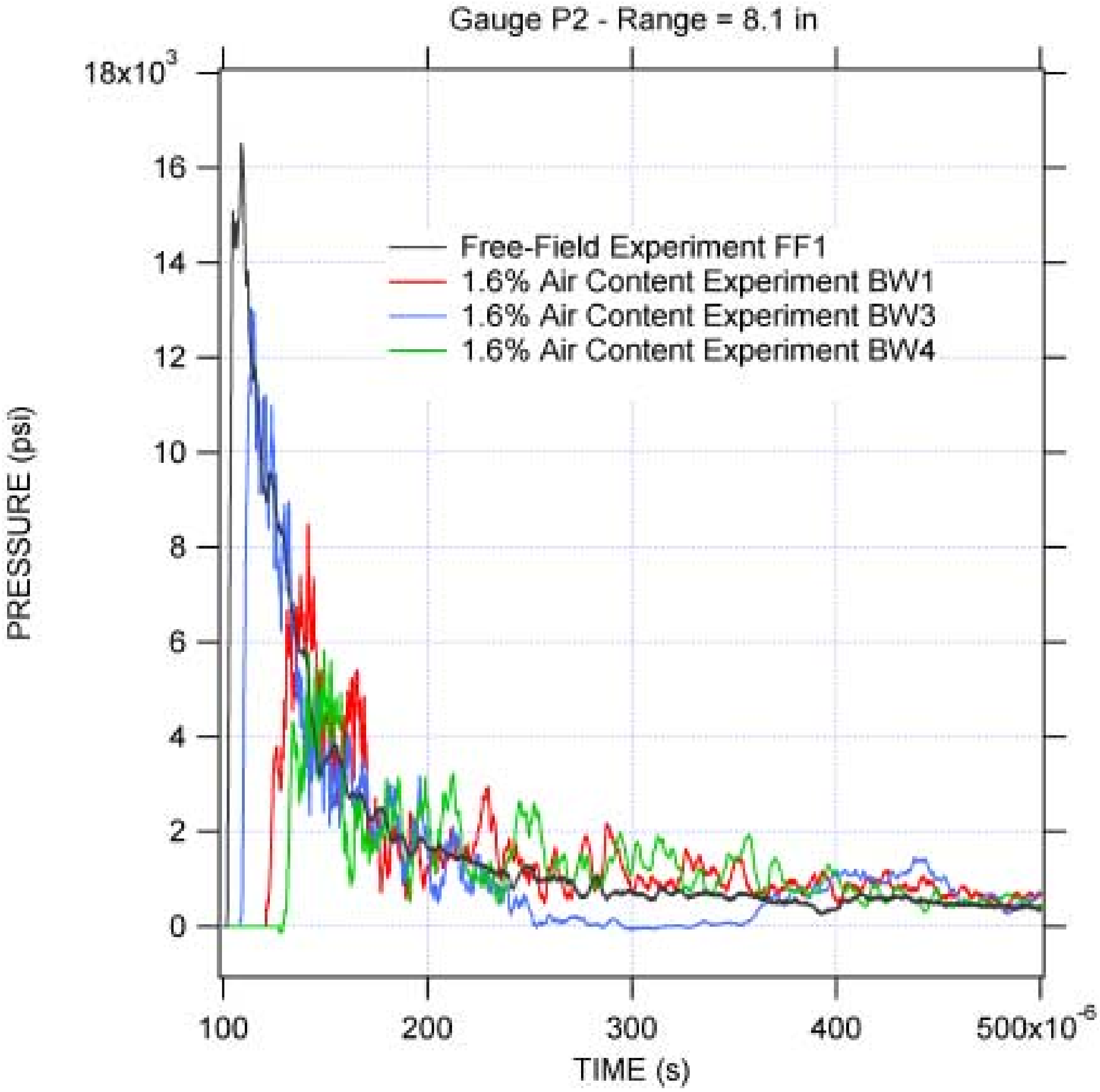

FIGURE 3-6. SHOCK PRESSURE-TIME HISTORY AT 8.1 IN. STANDOFF FROM CHARGE (400 μs TIME WINDOW)

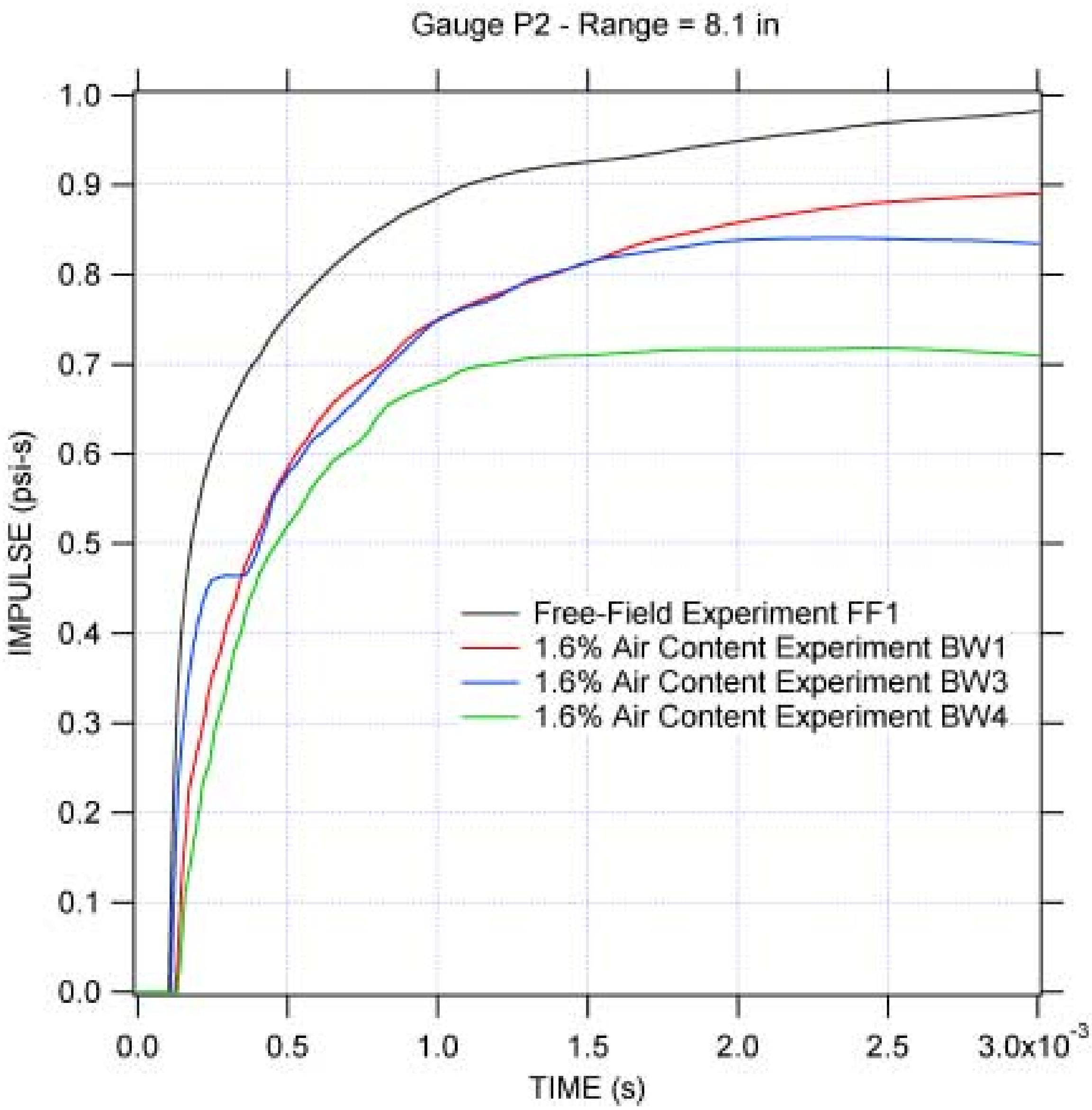

FIGURE 3-7. SHOCK IMPULSE-TIME HISTORY AT 8.1 IN. STANDOFF FROM CHARGE

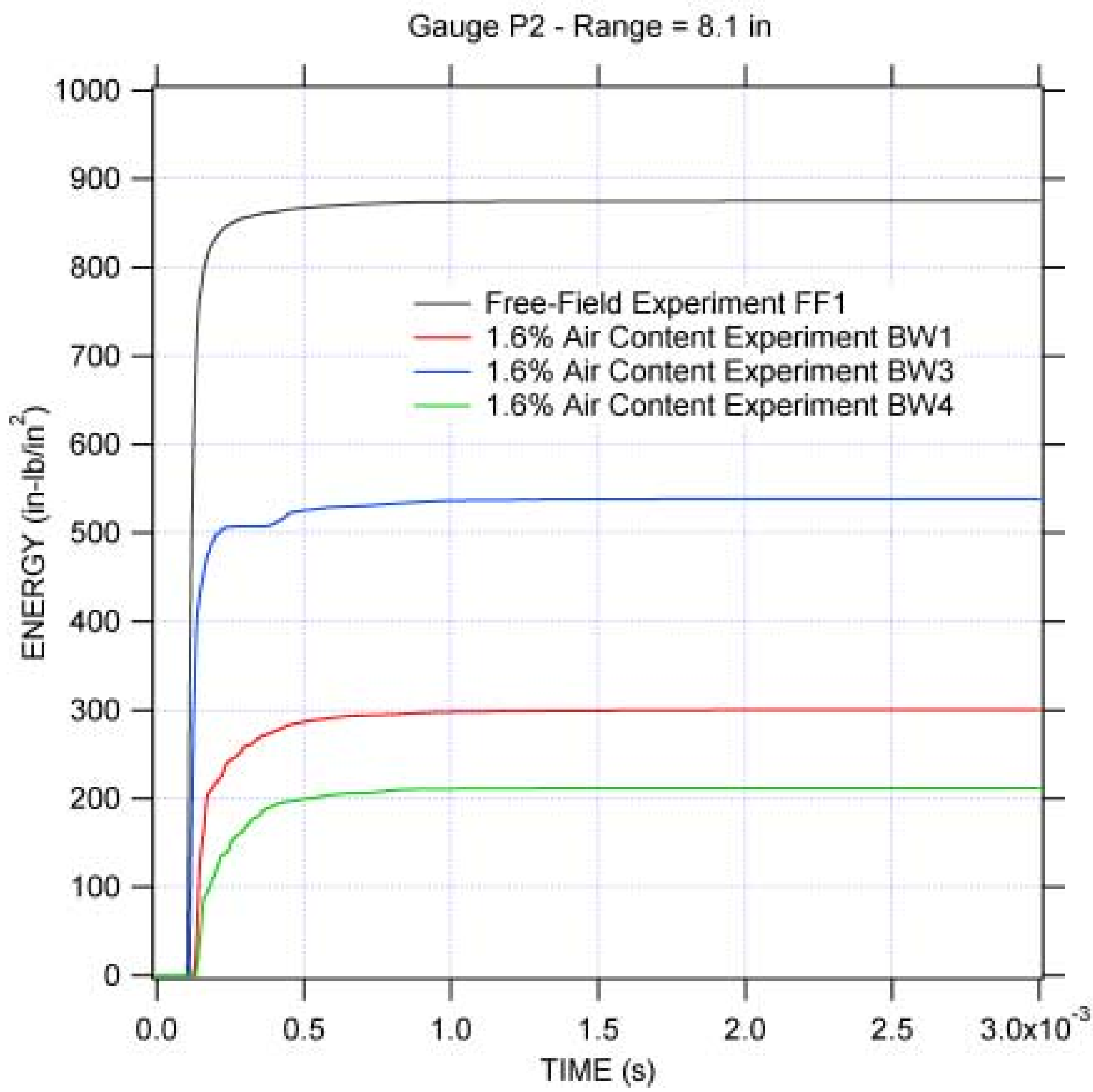

FIGURE 3-8. SHOCK ENERGY-TIME HISTORY AT 8.1 IN. STANDOFF FROM CHARGE

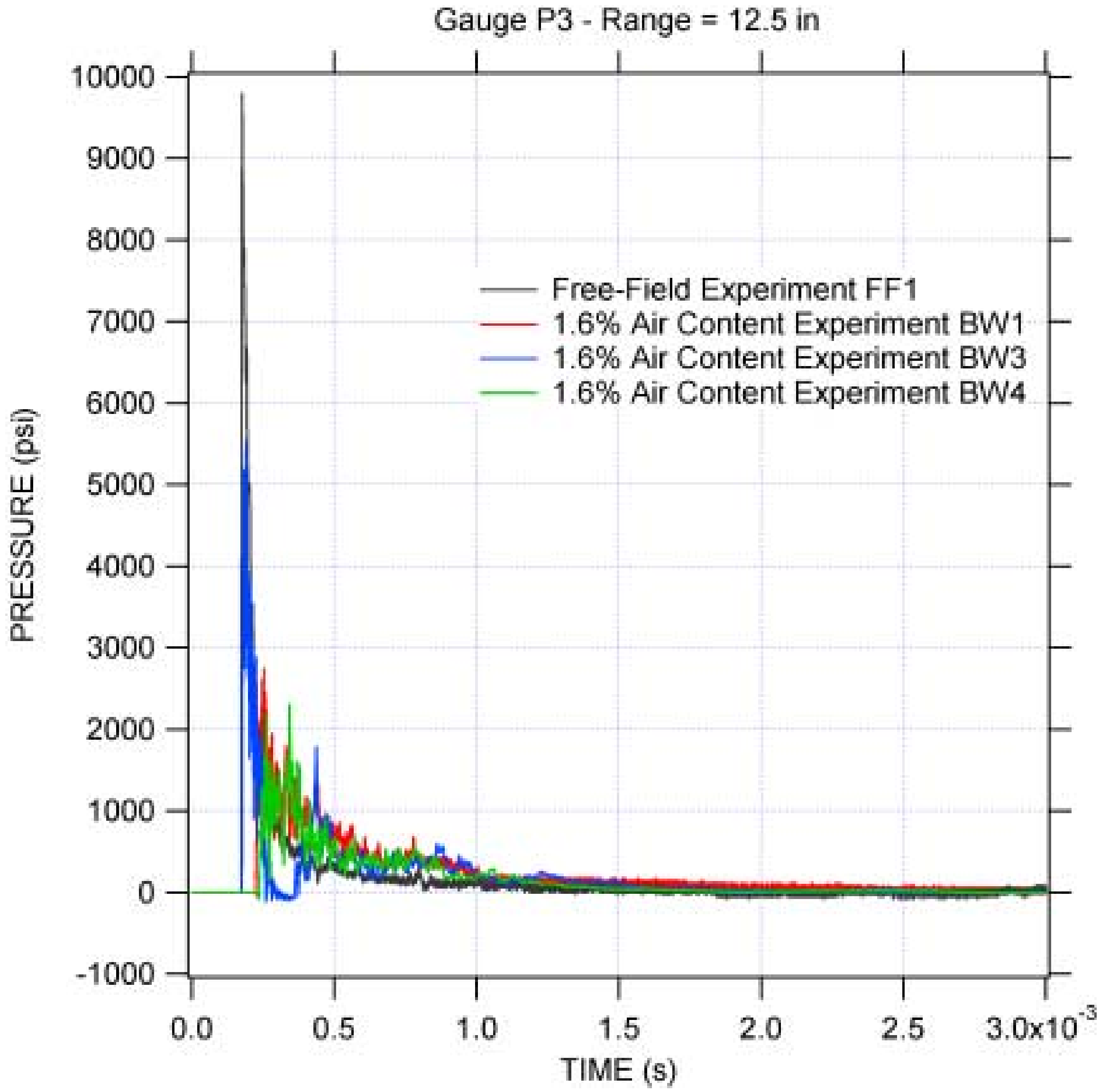

FIGURE 3-9. SHOCK PRESSURE-TIME HISTORY AT 12.5 IN. STANDOFF FROM CHARGE (3 ms TIME WINDOW)

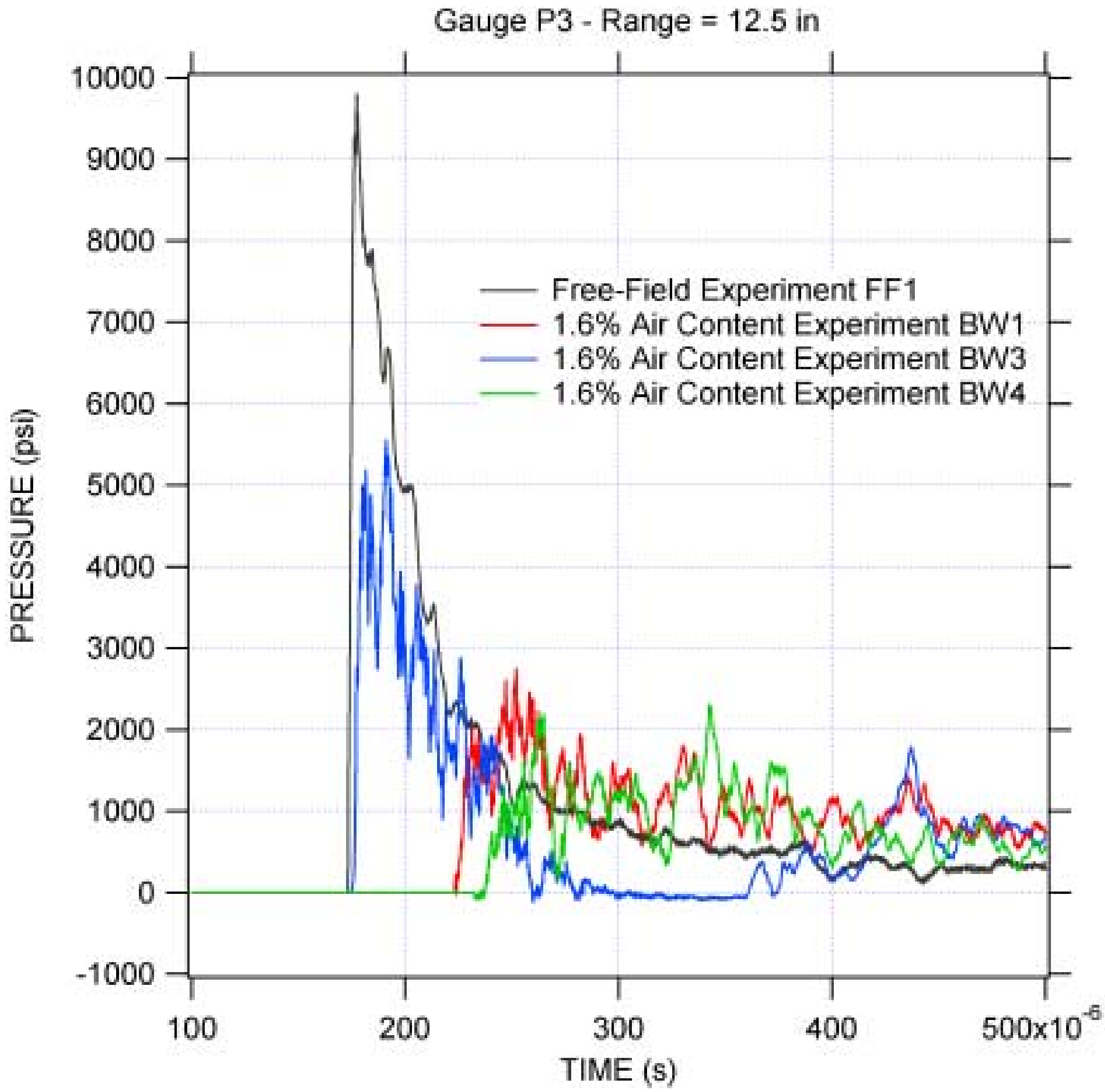

FIGURE 3-10. SHOCK PRESSURE-TIME HISTORY AT 12.5 IN. STANDOFF FROM CHARGE (400 μs TIME WINDOW)

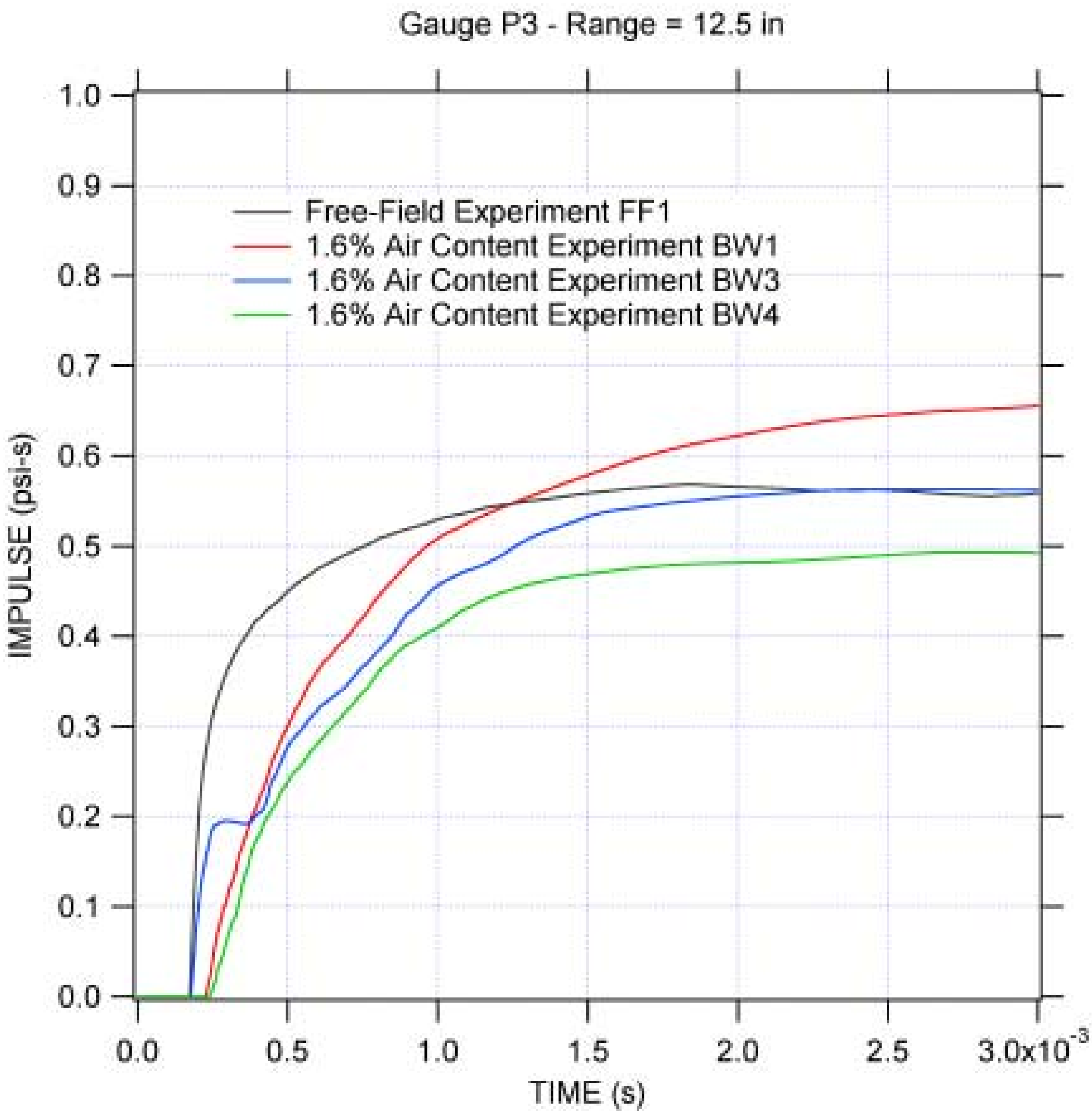

FIGURE 3-11. SHOCK IMPULSE-TIME HISTORY AT 12.5 IN. STANDOFF FROM CHARGE

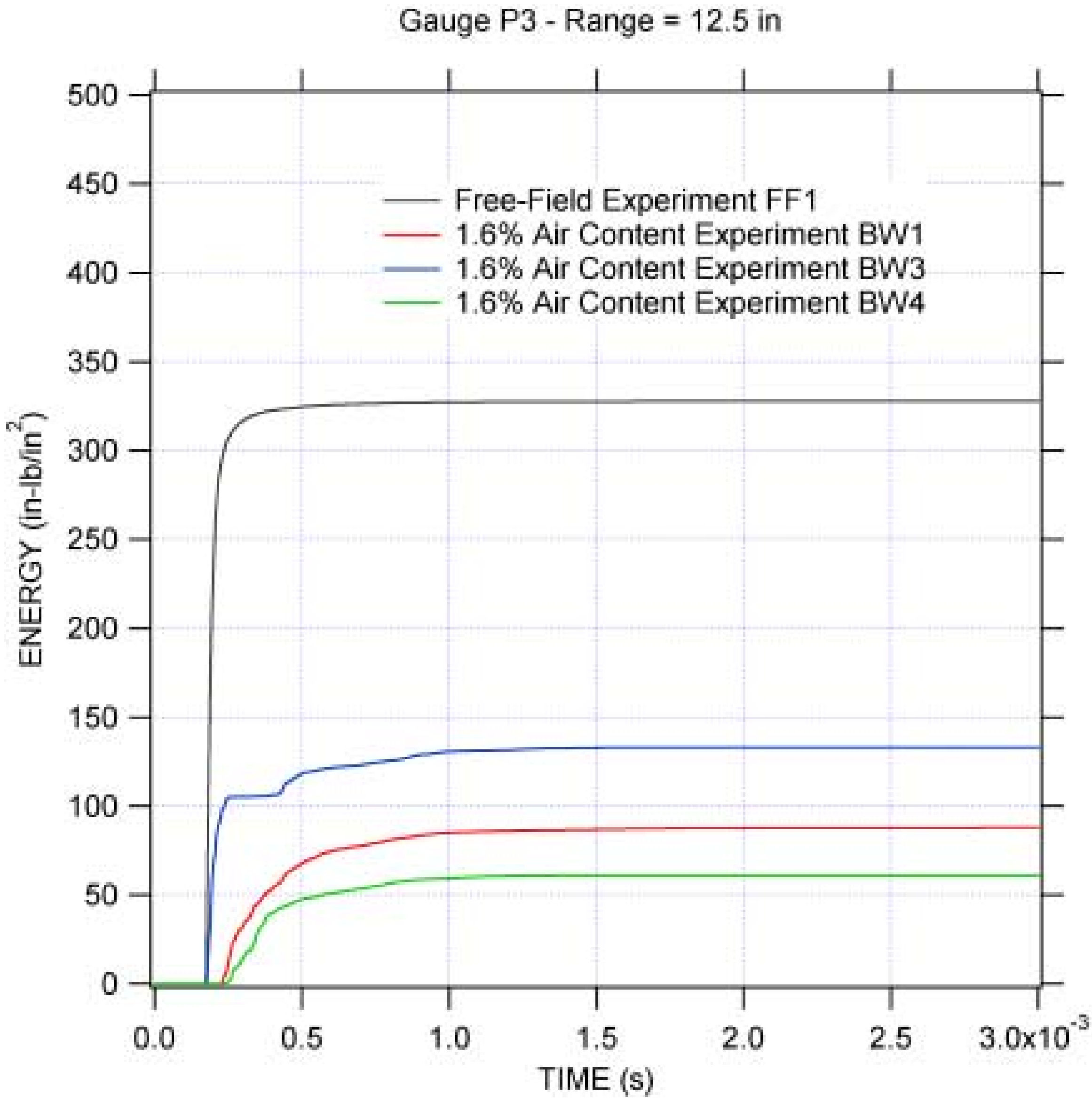

FIGURE 3-12. SHOCK ENERGY-TIME HISTORY AT 12.5 IN. STANDOFF FROM CHARGE

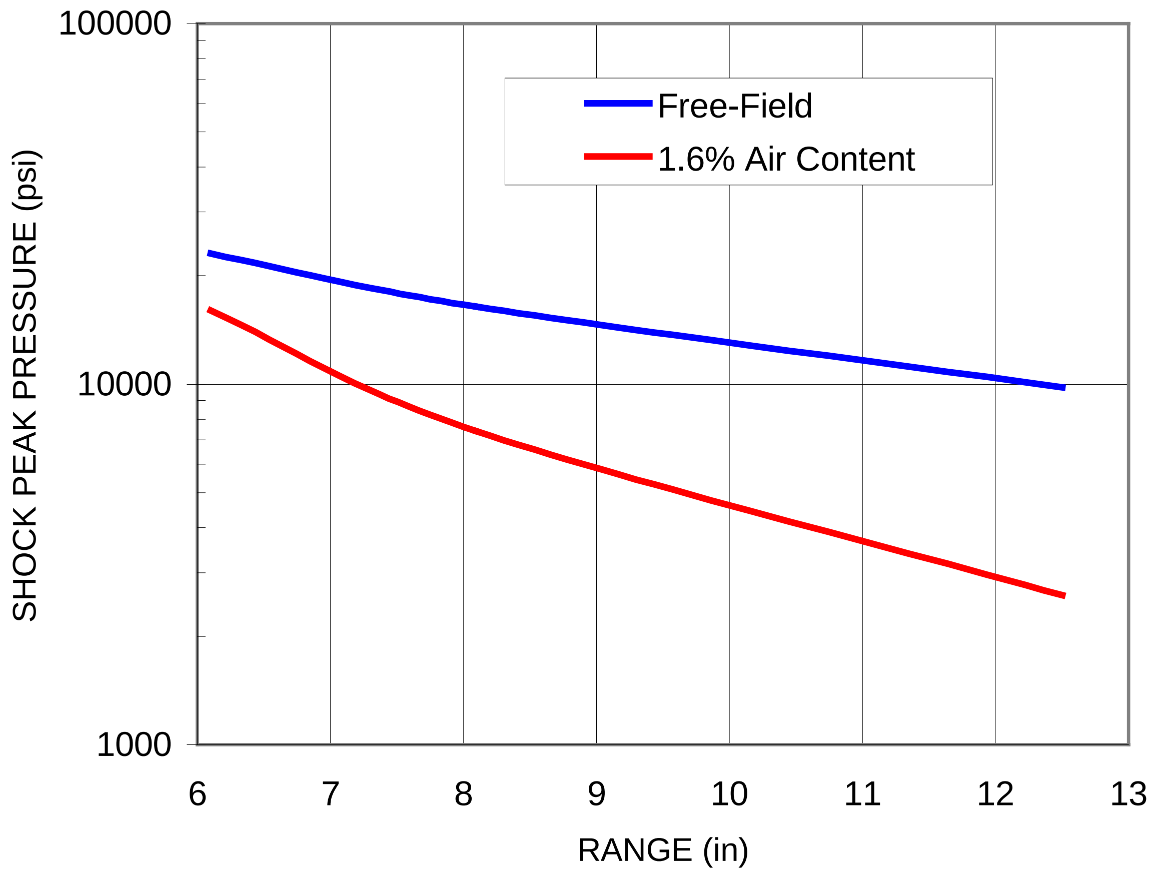

FIGURE 3-13. SHOCK PEAK PRESSURE ATTENUATION WITH RANGE IN AERATED WATER

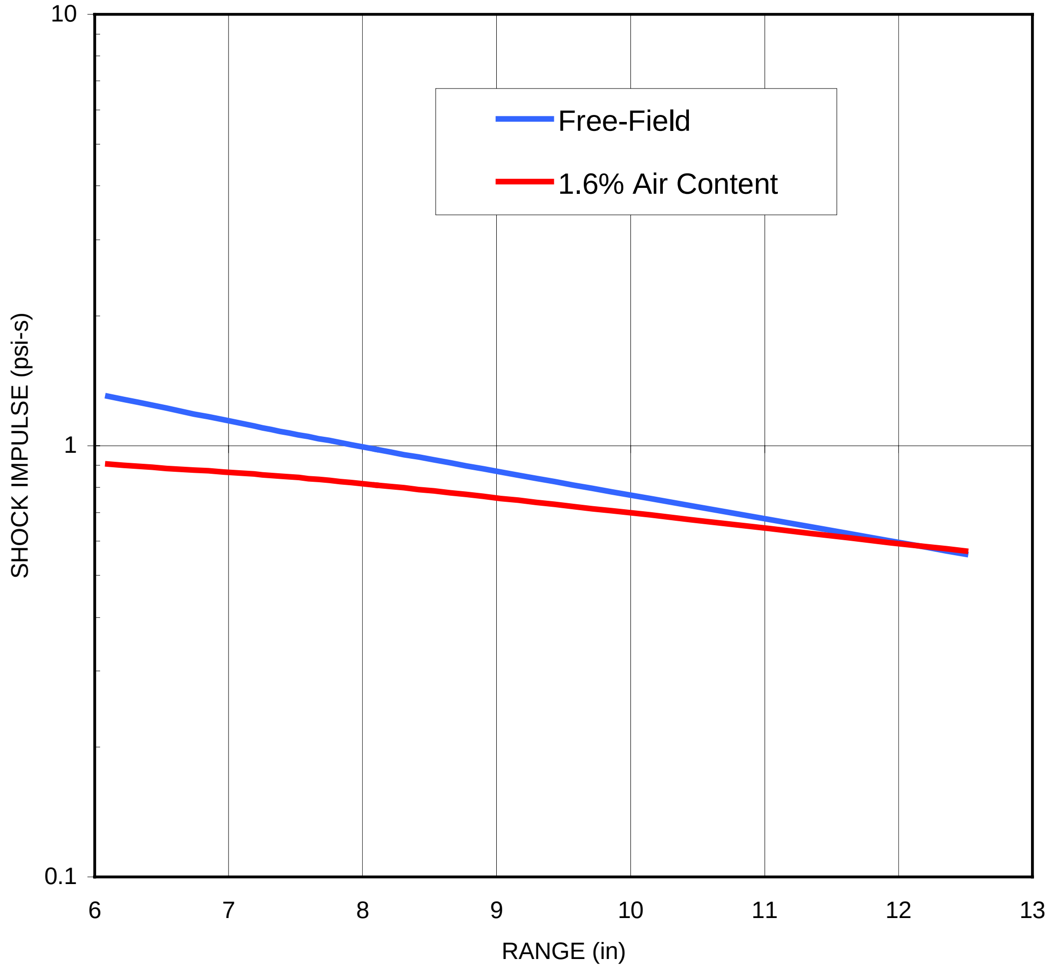

FIGURE 3-14. SHOCK IMPULSE ATTENUATION WITH RANGE IN AERATED WATER

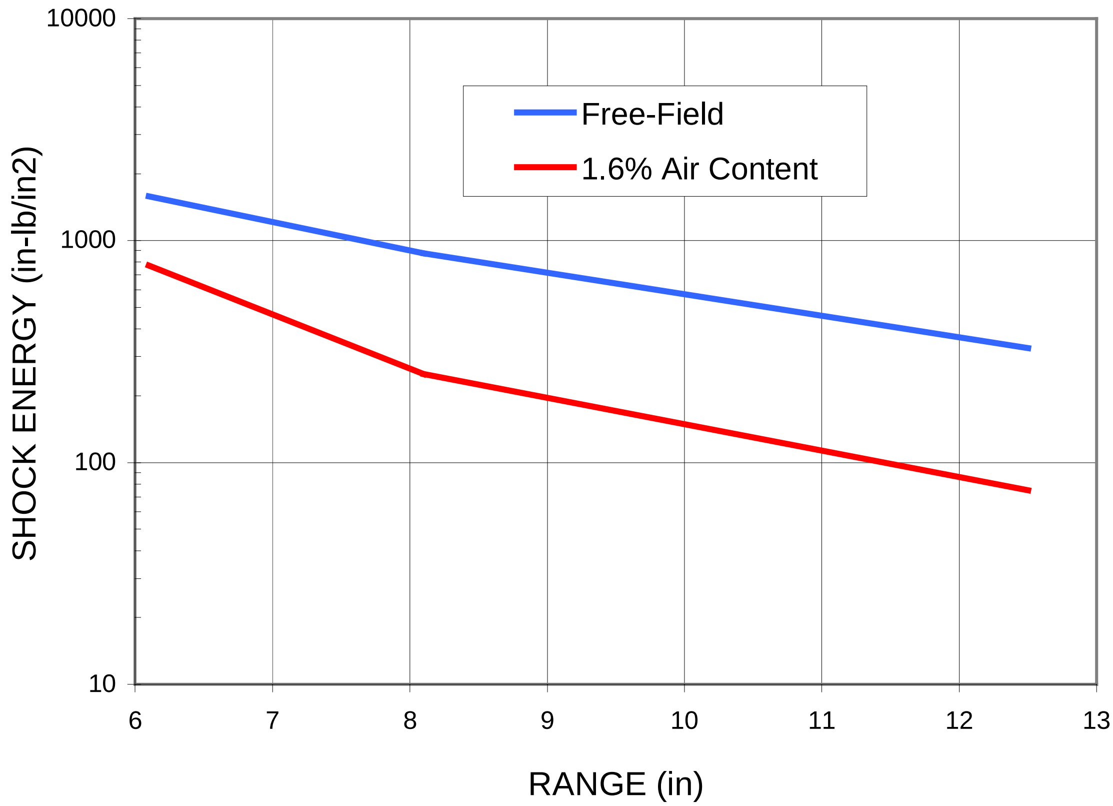

FIGURE 3-15. SHOCK ENERGY ATTENUATION WITH RANGE IN AERATED WATER

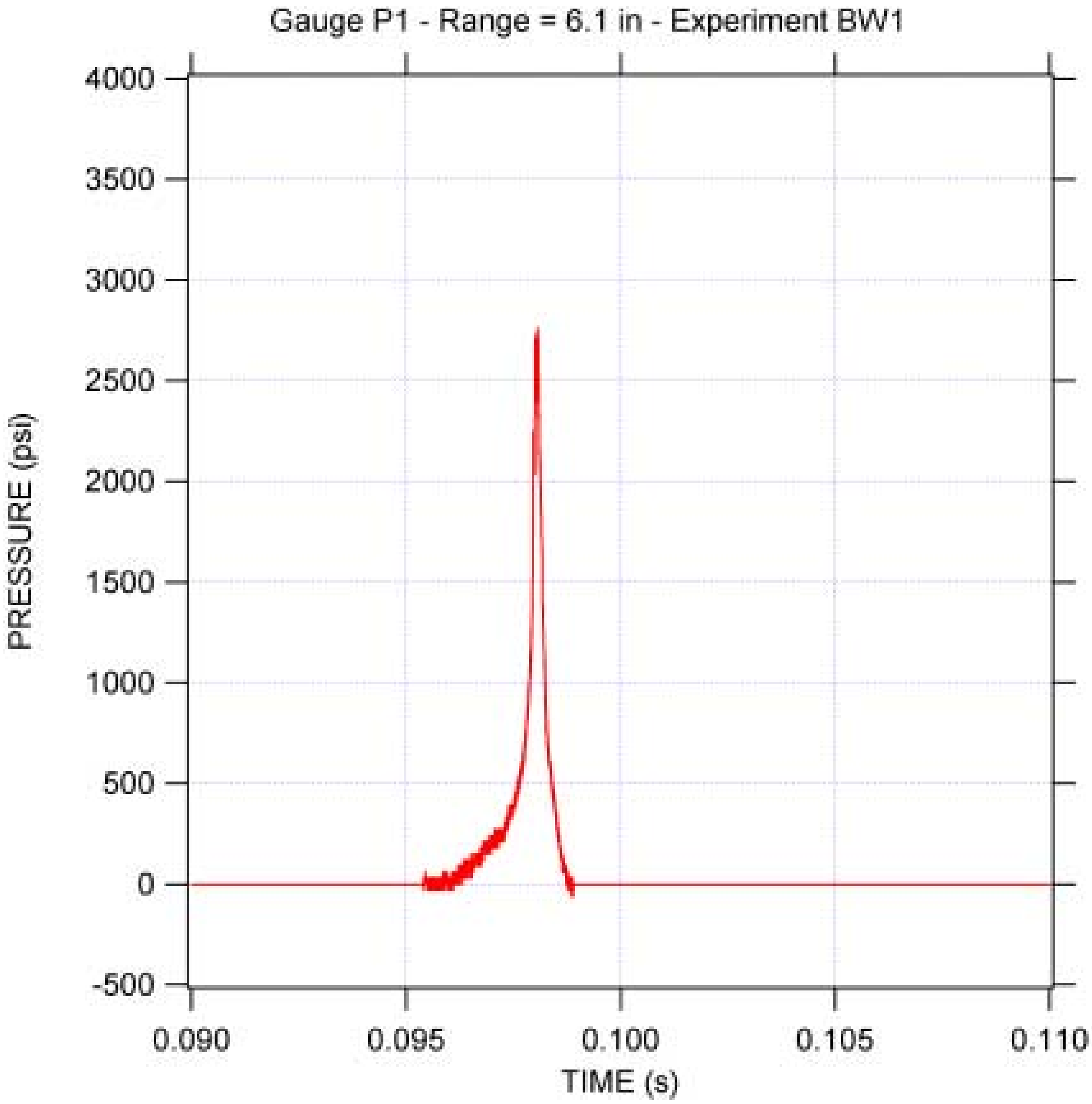

FIGURE 3-16. BUBBLE PRESSURE-TIME HISTORY AT 6.1 IN. STANDOFF FROM CHARGE

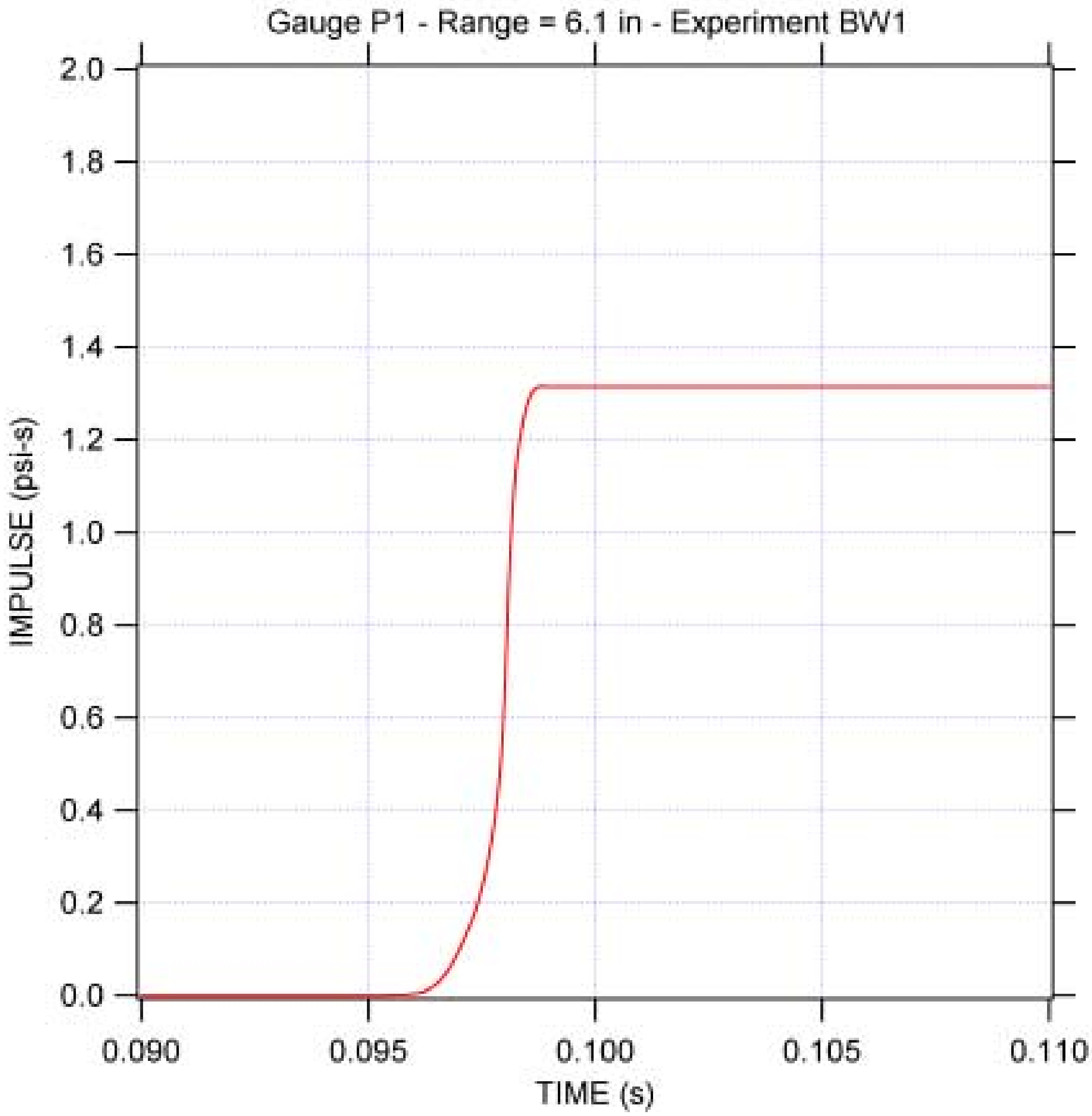

FIGURE 3-17. BUBBLE IMPULSE-TIME HISTORY AT 6.1 IN. STANDOFF FROM CHARGE

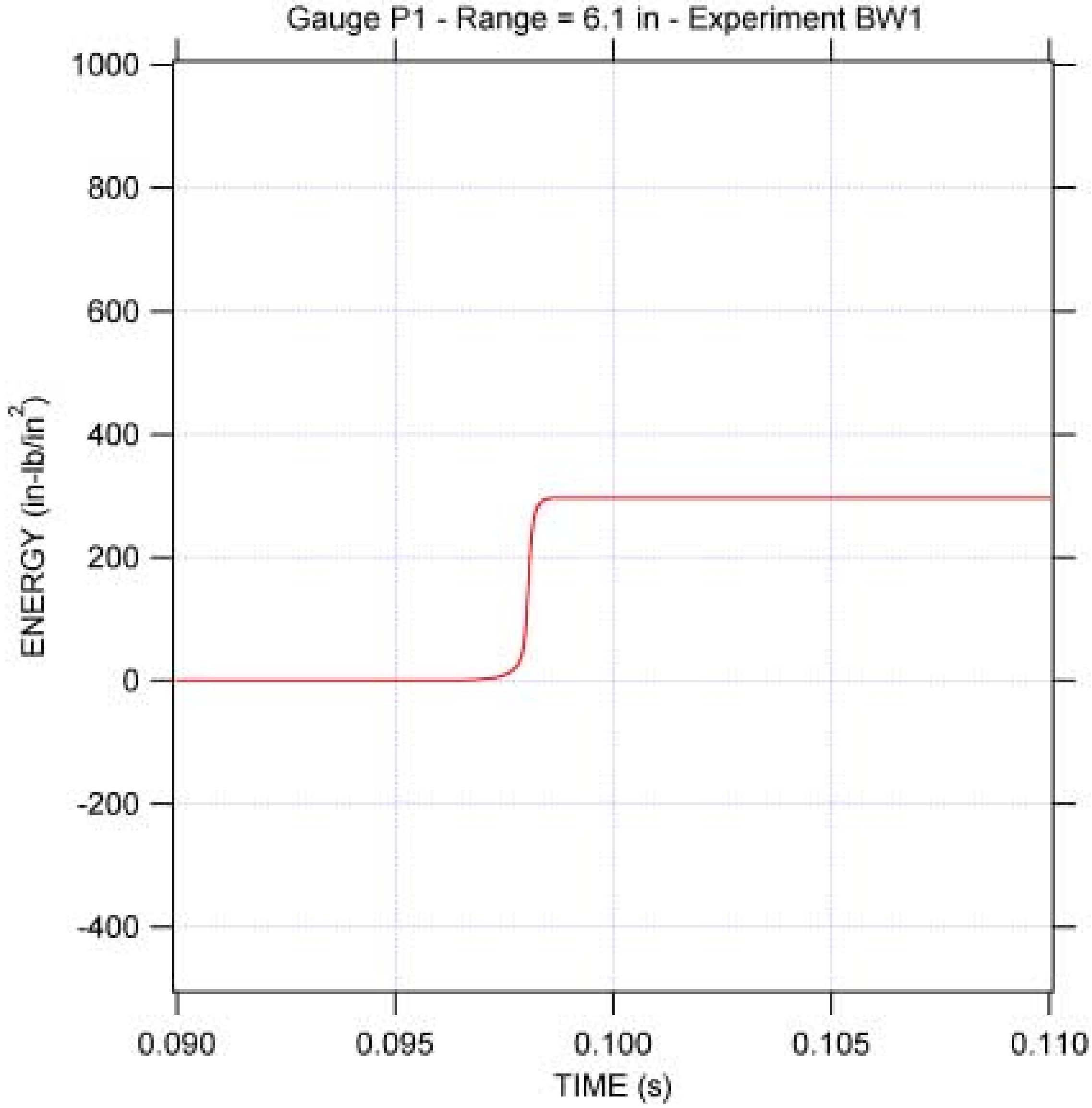

FIGURE 3-18. BUBBLE ENERGY-TIME HISTORY AT 6.1 IN. STANDOFF FROM CHARGE

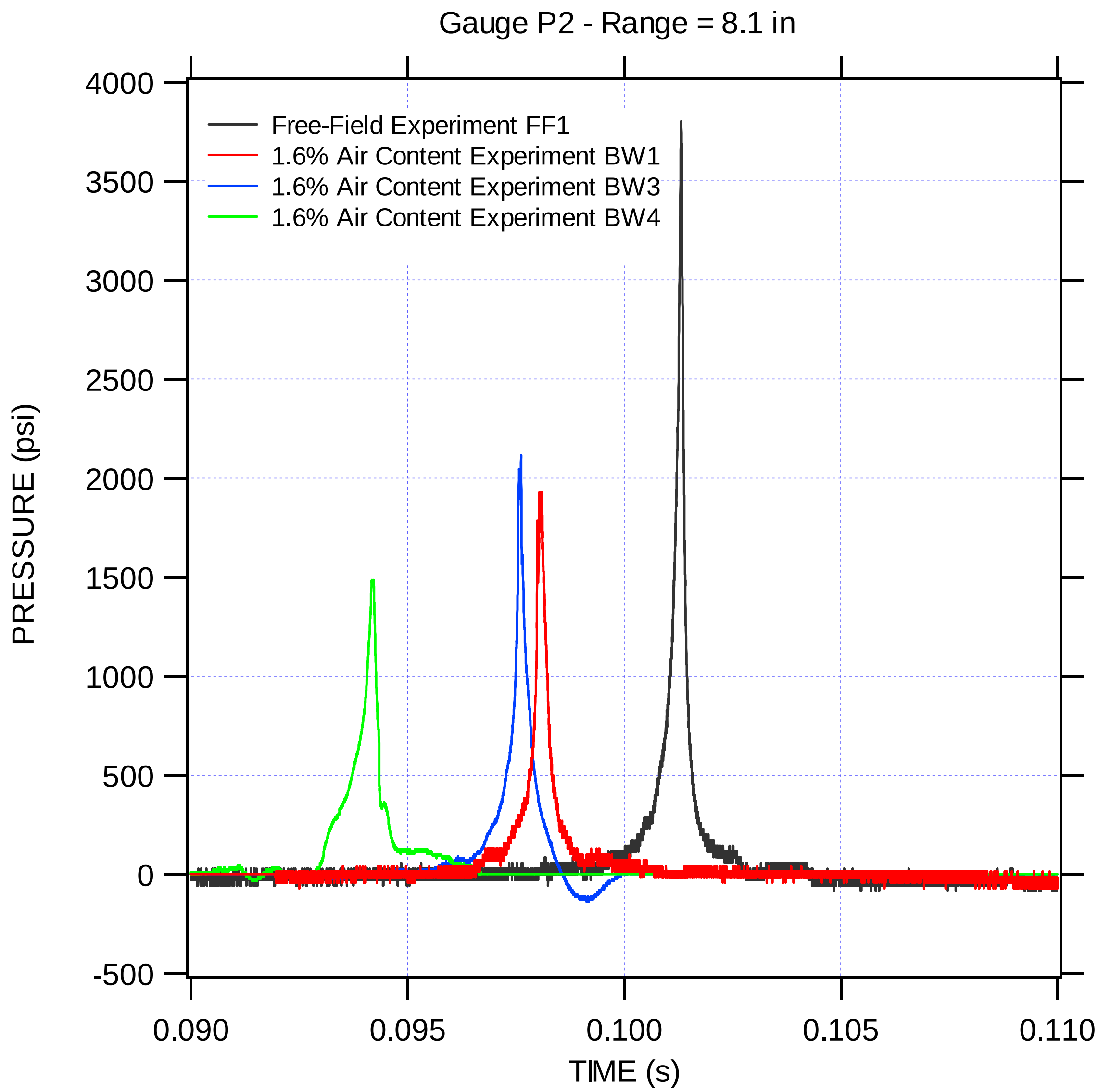

FIGURE 3-19. BUBBLE PRESSURE-TIME HISTORY AT 8.1 IN. STANDOFF FROM CHARGE

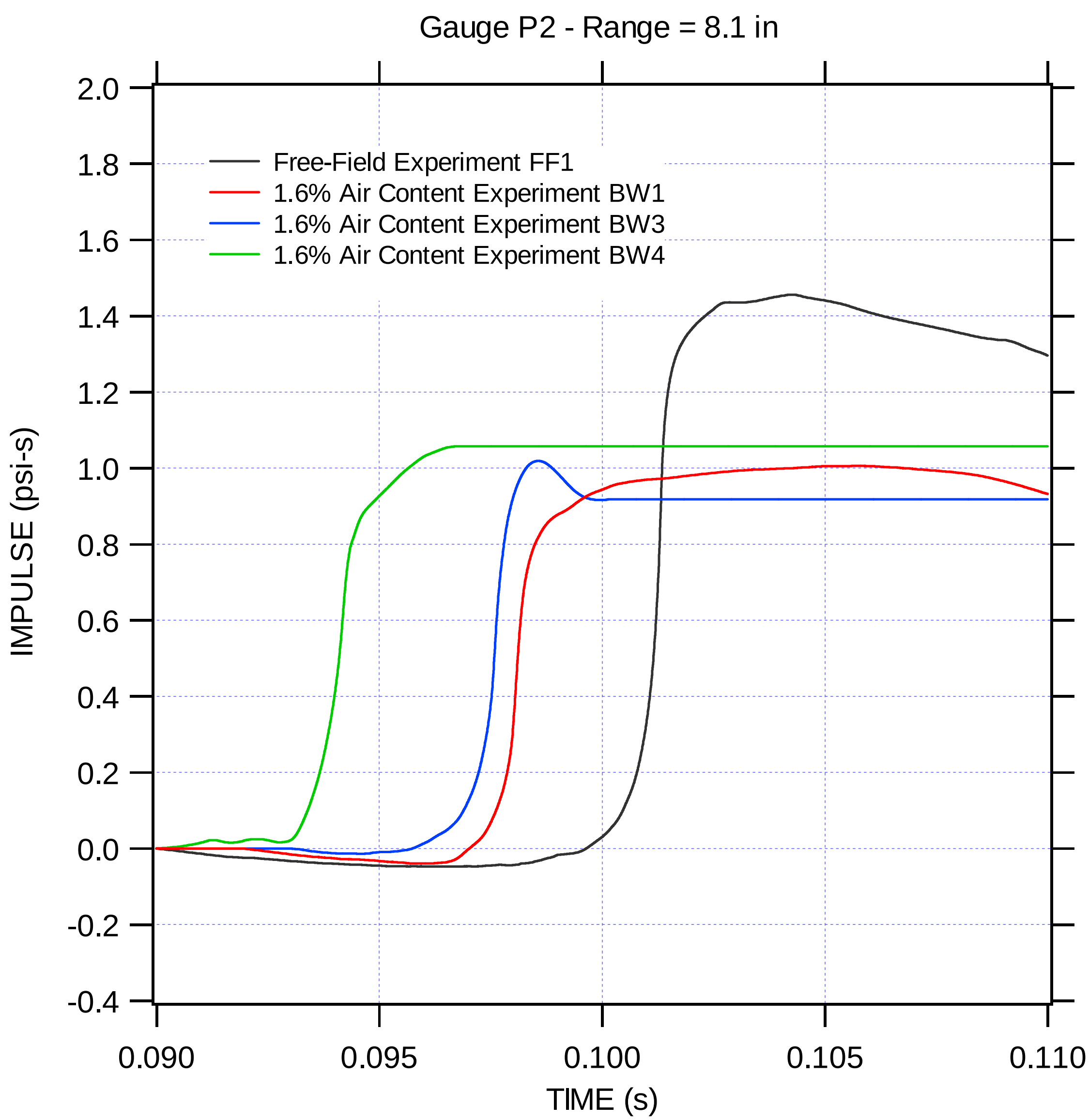

FIGURE 3-20. BUBBLE IMPULSE-TIME HISTORY AT 8.1 IN. STANDOFF FROM CHARGE

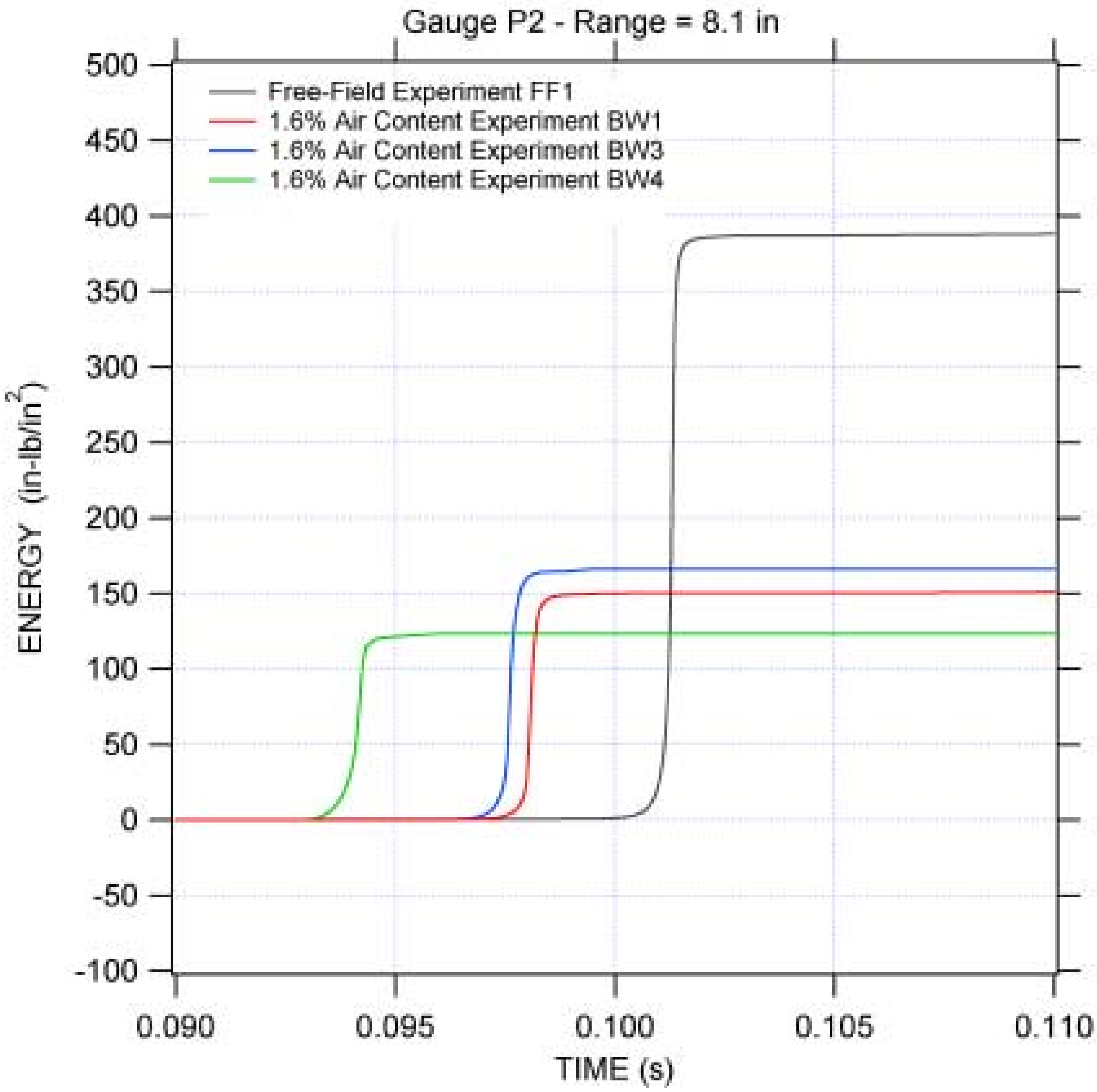

FIGURE 3-21. BUBBLE ENERGY-TIME HISTORY AT 8.1 IN. STANDOFF FROM CHARGE

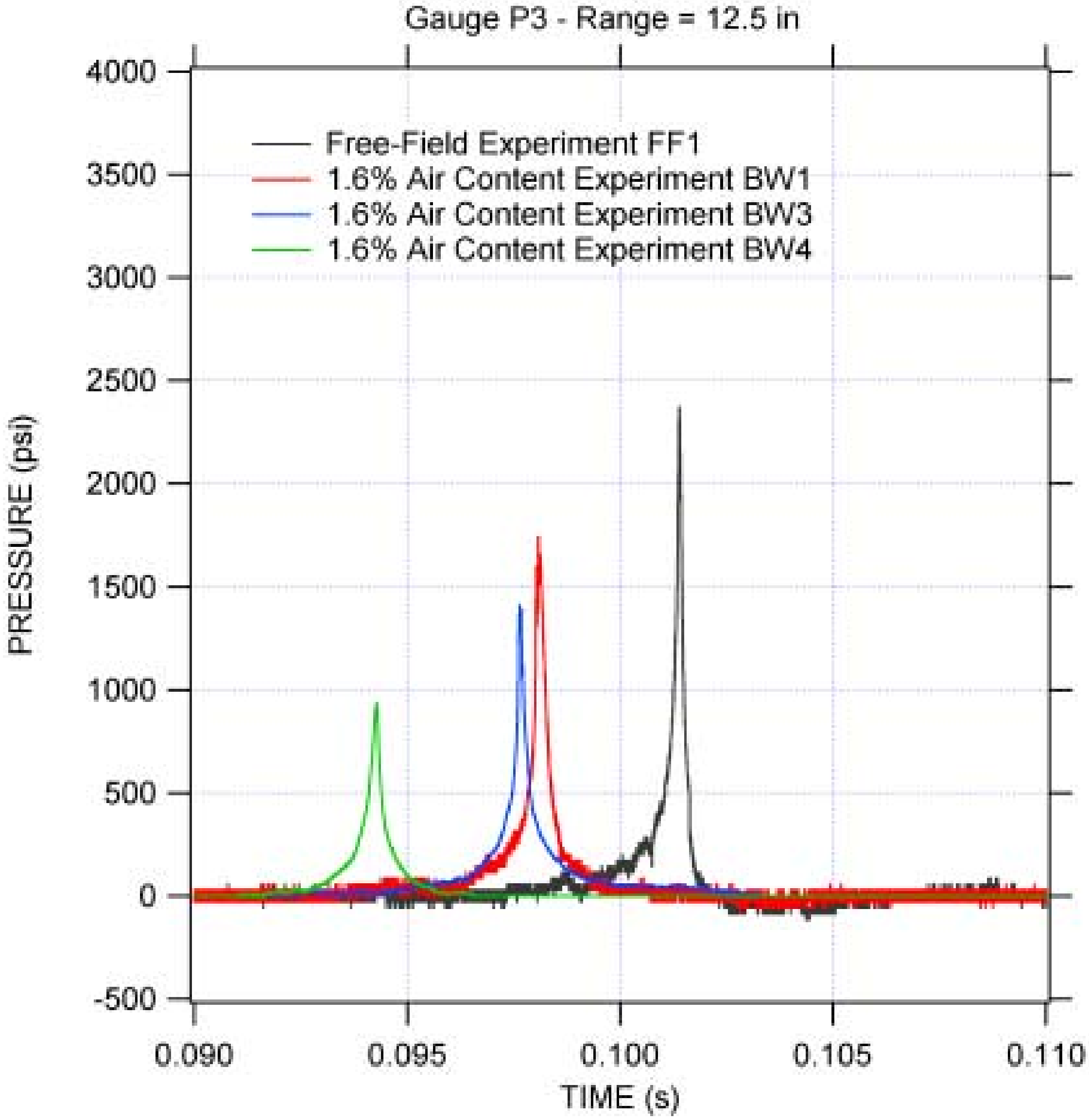

FIGURE 3-22. BUBBLE PRESSURE-TIME HISTORY AT 12.5 IN. STANDOFF FROM CHARGE

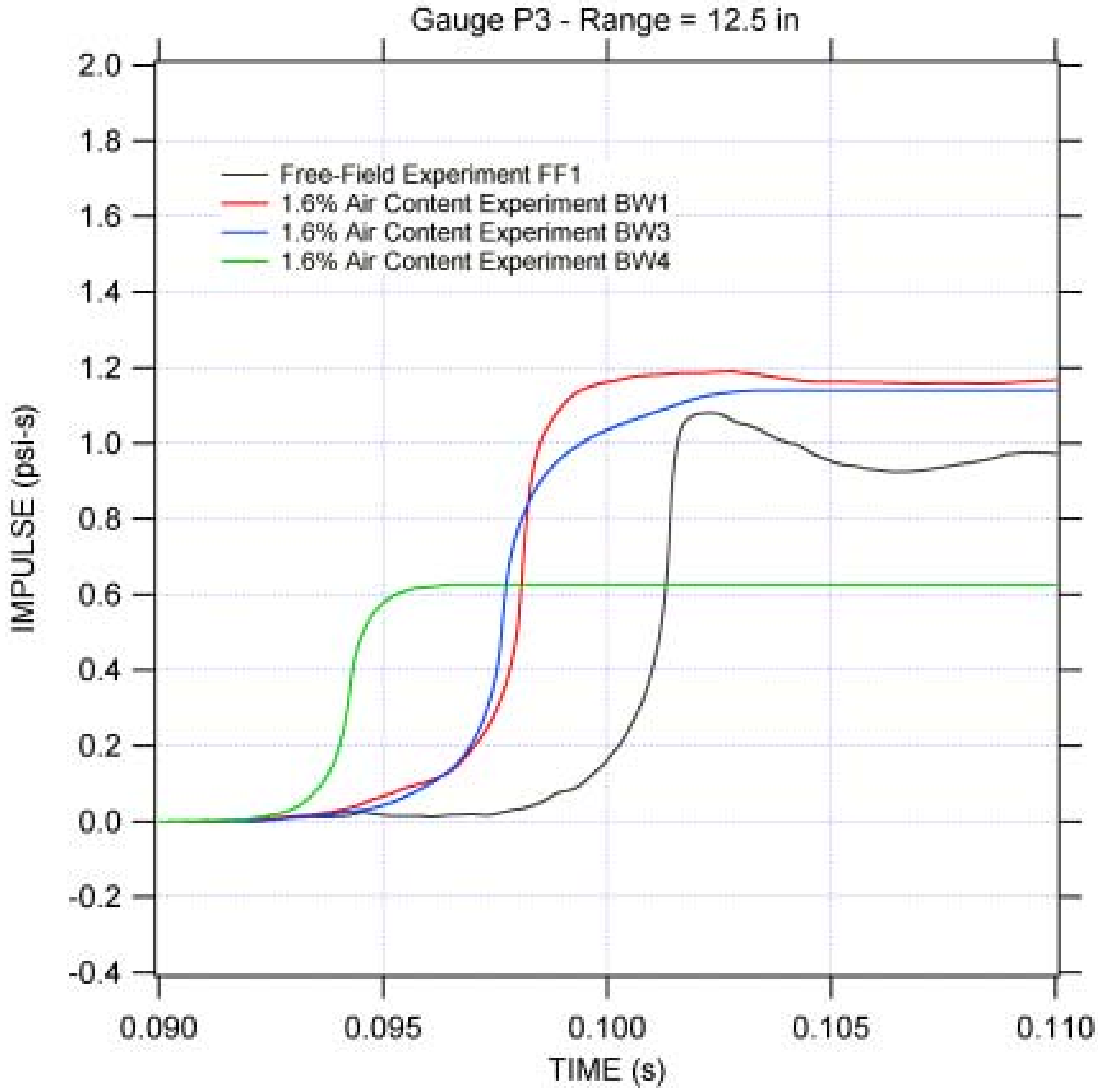

FIGURE 3-23. BUBBLE IMPULSE-TIME HISTORY AT 12.5 IN. STANDOFF FROM CHARGE

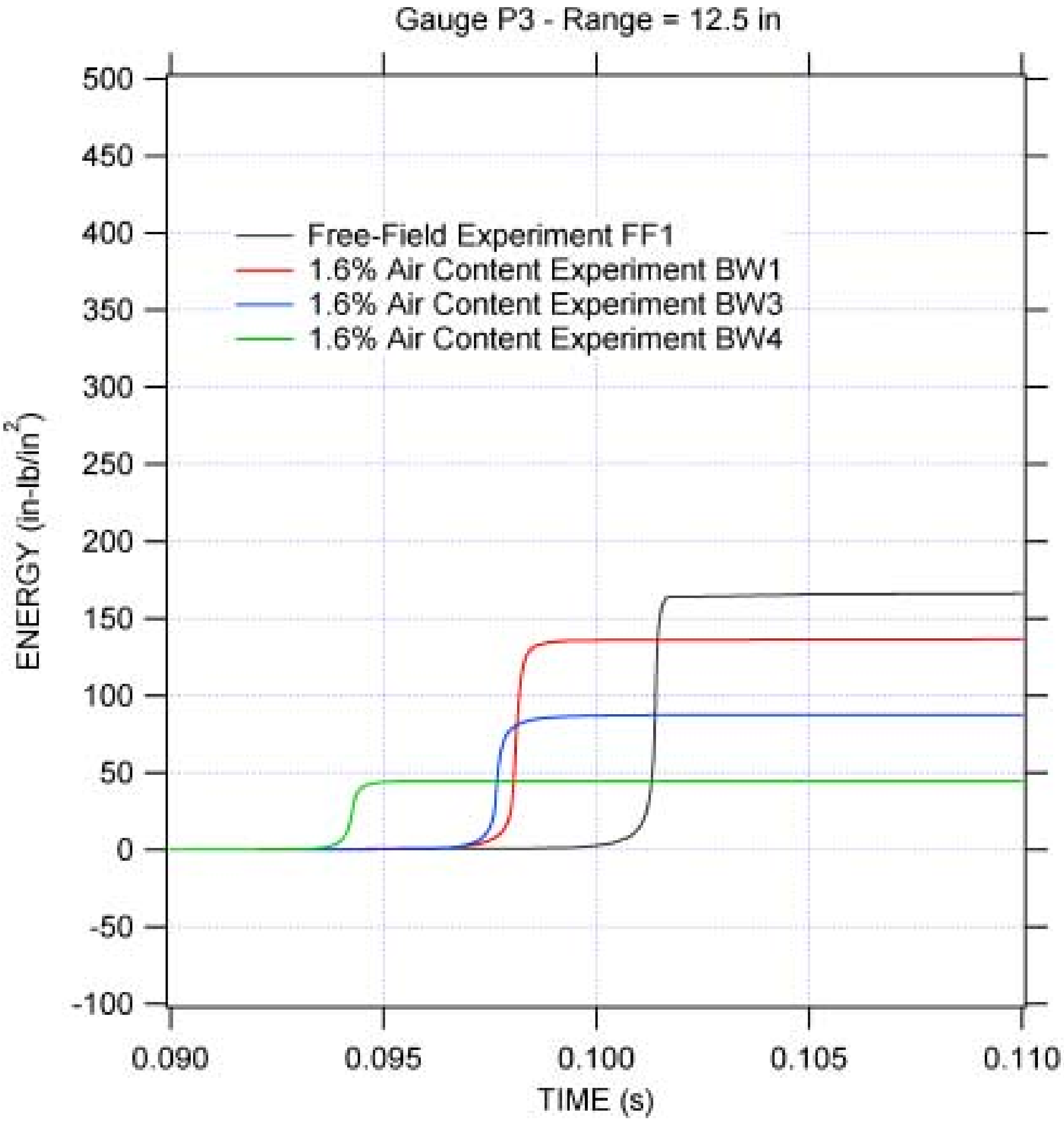

FIGURE 3-24. BUBBLE ENERGY-TIME HISTORY AT 12.5 IN. STANDOFF FROM CHARGE

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